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PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIA DA COMPUTAÇÃO

A SysML Profile for Smart City Applications

Dissertação de Mestrado

Layse Santos Souza

Programa de Pós-Graduação em Ciência da Computação/UFS

São Cristóvão – Sergipe

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Dissertação de Mestrado apresentada ao Programa de Pós-Graduação em Ciência da Computação da Universidade Federal de Sergipe como requisito parcial para a obtenção do título de mestre em Ciência da Computação.

Orientador: Prof. Dr. Michel dos Santos Soares

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Em 13 dias do mês de julho do ano de dois mil e vinte um, com início às 14h00min, realizou-se na Sala virtual https://meet.google.com/kni-rtks-dub. A Sessão Pública de Defesa de Dissertação de Mestrado do candidato **LAYSE SANTOS SOUZA**, que desenvolveu o trabalho intitulado: **"A SysML Profile for Smart City Applications",** sob a orientação da Prof. Dr. **Michel dos Santos Soares**. A Sessão foi presidida pelo Prof. Dr. **Michel dos Santos Soares** (PROCC/UFS), que após a apresentação da dissertação passou a palavra aos outros membros da Banca Examinadora, Prof. Dr. **Pedro Frosi Rosa** (UFU) e, em seguida, ao Prof. Dr. **Glauco de Figueiredo Carneiro** (PROCC/UFS). Após as discussões, a Banca Examinadora reuniu-se e considerou o(a) mestrando (a) **Aprovada** "*(aprovado/reprovado)*". Atendidas as exigências da Instrução Normativa 01/2017/PROCC, do Regimento Interno do PROCC (Resolução 67/2014/CONEPE), Resolução nº 25/2014/CONEPE e da Portaria nº 413 de 27 de maio de 2020 (Banca por videoconferência) que regulamentam a Apresentação e Defesa de Dissertação, e nada mais havendo a tratar, a Banca Examinadora elaborou esta Ata que será assinada pelos seus membros e pelo mestrando.

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Determination, courage and self-confidence are decisive factors for success. No matter what the obstacles and difficulties. If we are possessed of an unshakable determination, we will overcome them. Regardless of the circumstances, we must always be humble, modest and stripped of pride.
(Dalai Lama)

Abstract

A smart city is an urban center that integrates a variety of solutions to enhance infrastructure performance and achieve sustainable urban development. Urban roads are a critical infrastructure highly demanded by citizens and organizations interested in their deployment, performance, and safety. Urban traffic signal control is a major and challenging problem in the real world, which aims to monitor and enhance traffic congestion. Therefore, the deployment of traffic signals for vehicles or pedestrians at a junction is a complex activity, as it is necessary to establish rules to control the flow of vehicles and pedestrians. Also, traffic flow at intersections changes constantly, depending on weather conditions, day of the week, and period of the year, as well as road works and accidents that further influence complexity and performance. This thesis first describes SmartCitySysML, a proposed profile that adapts SysML with special elements that are specific to smart cities. In addition, an extension of the SmartCitySysML profile to the design of the dimensions of smart cities is proposed. Finally, integration of models is performed, that is, the integration of the SmartCitySysML profile with Petri Net to separately model the basic architectural elements (sensor, controller, and actuator) of an urban traffic control system as sub-models to describe the behavior of each element, and the integration of the SmartCitySysML profile with Timed Coloured Petri Nets (TCPN) for modeling, simulation, and verification of properties of an urban traffic signal control system. CPN tools allow the evaluation of the model behavior through simulation and property verification and perform a simulation-based performance. Model simulation allows observing the behavior of the system under conditions that would be difficult to organize in a truly controlled environment. Consequently, a preliminary evaluation can be performed in the early stages of system development, significantly reducing costs of improvements and increasing quality of the final product.

Keywords: Smart Cities, SysML, Petri Net, Timed Coloured Petri Nets, Urban Traffic Signal Control, Model Integration, Model Simulation, Formal Verification.

Resumo

Uma cidade inteligente é um centro urbano que integra uma variedade de soluções para melhorar o desempenho da infraestrutura e alcançar um desenvolvimento urbano sustentável. As estradas urbanas são uma infraestrutura crucial altamente exigida pelos cidadãos e organizações interessadas em sua implantação, desempenho e segurança. O controle de sinais de trânsito urbano é um problema importante e desafiador no mundo real, que visa monitorar e melhorar o congestionamento de trânsito. Portanto, a implantação de semáforos para veículos ou pedestres em um cruzamento é uma atividade complexa, pois é necessário estabelecer regras para controlar o fluxo de veículos e pedestres. O fluxo de tráfego no cruzamento muda constantemente, dependendo das condições climáticas, dia da semana e período do ano, assim como obras e acidentes rodoviários que influenciam ainda mais a complexidade e o desempenho. Esta dissertação descreve primeiro o SmartCitySysML, um perfil proposto que adapta a SysML com elementos especiais que são específicos para cidades inteligentes. Depois, é elaborada uma extensão do perfil SmartCitySysML para o design das dimensões das cidades inteligentes. Em seguida, é realizada a integração de modelos, ou seja, a integração do perfil SmartCitySysML com Redes de Petri para modelar separadamente os elementos arquiteturais básicos (sensor, controlador e atuador) de um sistema de controle de tráfego urbano como sub-modelos para demonstrar o comportamento de cada elemento, e a integração do perfil SmartCitySysML com Redes de Petri Colorida Temporizada (TCPN) para modelagem, simulação e verificação de propriedades do sistema de controle de sinais de trânsito urbano. As ferramentas CPN permitem avaliar o comportamento do modelo por meio de simulação e verificação de propriedades e realizar um desempenho baseado em simulação. A simulação de modelos permite observar o comportamento do sistema sob condições que seriam difíceis de organizar em um ambiente realmente controlado. Consequentemente, uma avaliação preliminar pode ser realizada nos estágios iniciais de desenvolvimento do sistema, reduzindo significativamente os custos de melhorias e aumentando a qualidade do produto final.

Palavras-chave: Cidades Inteligentes, SysML, Redes de Petri, Redes de Petri Coloridas Temporizadas, Controle de Sinais de Trânsito Urbano, Modelo de Integração, Modelo de Simulação, Verificação Formal.

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List of abbreviations and acronyms

BDD	Block Definition diagram
CPN	Coloured Petri Nets
FR	Functional Requirements
IBD	Internal Block diagram
ICCSA	International Conference on Computational Science and Its Applications
ICT	Information and Communication Technologies
INCOSE	International Council on Systems Engineering
IoT	Internet of Things
OMG	Object Management Group
REQ	Requirements diagram
SD	Sequence diagram
SysML	Systems Modeling Language
TCPN	Timed Coloured Petri Nets
UML	Unified Modeling Language

Contents

1 Introduction

The impact of the digital revolution in a world of accelerated urbanization supports the growth of the concept of smart cities. Smart cities are safe, efficient, and environmentally friendly urban centers with infrastructure designed, built, and maintained through technology, for example, databases, systems, sensors, controllers, and actuators. In a smart city the factors community, technology, and politics are the drivers associated with productivity, sustainability, accessibility, welfare, habitability, and governance (YIGITCANLAR et al., 2018).

Smart cities propose to bring together integrated and autonomous systems with the infrastructure of cities to improve quality of life of their citizens. In these cities, both existing systems and infrastructures are extensive and critical to their functioning, as they share reality from different perspectives, e.g., geographic location, artifacts, and domains (CLEMENT; MCKEE; XU, 2017).

In smart cities, one challenge is the development of more specific systems, that is, systems that require new Information and Communication Technology (ICT) infrastructure with components and services that provide the basis to sustain all systems. An efficient and sustainable ICT infrastructure facilitates the development of innovative systems (KHATOUN; ZEADALLY, 2016), (ISMAGILOVA et al., 2019).

ICT infrastructure plays an important role in improving people's quality of life, transforming the relationship between local entities, businesses, and citizens, and efficiently delivering urban services. Although these services can be handled independently, they are interdependent, mainly because of the need to use processes, resources, and networks with different functionalities (SCHOONENBERG; FARID, 2017).

These services are designed to improve citizens' quality of life, e.g., urban traffic control, emergency and home medical assistance, energy monitoring, and evacuation routes in case of disasters. Currently, these services have critical access and are deployed near end users, i.e., citizens (ABREU et al., 2017).

Different functionalities of services need to be integrated to achieve communication between systems, sensors, controllers, actuators, other software, services, and people using the Internet of Things (IoT) as a tool to collect and store data. Therefore, it is necessary to provide a system architecture that has high level of scalability and interoperability to ensure the continuity of these services (ABREU et al., 2017), (DIACONITA; BOLOGA; BOLOGA, 2018).

Integration of services with the system architecture in smart cities is a major challenge that requires creation of models to provide an appropriate level of abstraction, i.e., bringing together different views and perspectives for the process of developing applications in a smart city (DIACONITA; BOLOGA; BOLOGA, 2018), (KURYAZOV; WINTER; SCHÖNBERG, 2018).

In the process of developing applications for smart cities, profiles are appropriate for modeling system-based architectures responsible for the control of ICT infrastructures (FARIAS et al., 2017), (MOHSIN; JANJUA, 2018). A UML profile comprises extensions of UML metaclasses, such as classes or properties, in the form of stereotypes. Stereotypes define formal restrictions that allow automatic validation of models based on profiles (RADEMACHER; SACHWEH; ZÜNDORF, 2018).

UML profiles have been proposed by research groups and industry to model systems for smart cities, including, for example, Systems Modeling Language (SysML) (FRIEDENTHAL; MOORE; STEINER, 2014), Modeling and Analysis of Real-Time and Embedded Systems (MARTE) (KHAN; MALLET; RASHID, 2019), UML Profile for Schedulability, Performance and Time (SPT) (XU; WOODSIDE; PETRIU, 2003), Business Process Modeling Notation (BPMN) (KALENKOVA et al., 2017), Service Oriented Architecture Modeling Language (SoaML) (RHAZALI; HADI; MOULOUDI, 2016), and GeoProfile (FERREIRA; STEMPLIUC; LISBOA-FILHO, 2014).

SysML has been used for high-level modeling applied to systems, as well as the basis for the design of software solutions for smart cities. One can mention the support for specification, analysis, design, verification, and validation of systems (FRIEDENTHAL; MOORE; STEINER, 2014) that include hardware, software, information, processes, people, and procedures (BIGGS; SAKAMOTO; KOTOKU, 2016).

One of the problems of modeling is the verification of models, i.e., to investigate whether a model meets specifications, properties and behaviors so that the software development is based on correct models, which will improve systems safety and quality (BARESI et al., 2015), (ABDULKHALEQ; WAGNER; LEVESON, 2015).

A possible way to verify models at the design level is through the good properties verified by algorithms proposed by formal methods. Petri Net is a formal method that allows modeling, graphically and mathematically, systems that have elements characterized as asynchronous, simultaneous, parallel, distributed, non-deterministic and/or stochastic by providing communication about the behavior of systems, identifying conflicts, cycles, unexpected behaviors and *deadlocks*

(MURATA, 1989).

In this thesis, it is proposed to extend SysML to create a profile for smart cities. This profile includes the needs of the applications and elements of smart cities, for example, stakeholders, requirements, solutions, processes, and dimensions as native SysML components. Modeling of the application domain can characterize the various types of infrastructure services promoting consistency and integrity of the system. Verification of models with Petri Net can prove good behavioral and structural properties of the model, and reveal possible model failures, especially behavioral models.

1.1 Problem and Motivation

The design and maintenance of smart city infrastructures are crucial activities for the efficient and effective use of a city infrastructure. Infrastructures' high complexity leads to the need to apply Information and Communication Technologies (ICT) and processes in their control and management to the architecture and design of software systems.

Considering smart city infrastructure applications, extending SysML to include smart city elements as native SysML components and adapting the language to represent smart city-related elements are important factors. This transformation allows for better modeling of the infrastructures that perform smart operations, for example, modeling the infrastructures of a traffic signal control system developed through this transformation ensures that mobility occurs in a safe and healthy environment.

Road infrastructure is highly demanded by citizens and organizations. The introduction of new infrastructure on a highway is important, but presents disadvantages, since the construction of new road infrastructure is limited due to environmental, social, and financial constraints.

The implementation of software systems responsible for the control of ICT infrastructures is a possible solution for traffic signal control. Traffic signal control is an important and challenging problem in the real world. Traffic signals are one of the main tools to control and manage the flow of vehicles and pedestrians, e.g., traffic congestion can provide potential solutions to ensure better, safe, and efficient transport and citizen satisfaction (YUAN, 2020).

The deployment of traffic signals for vehicles or pedestrians at an intersection is complex, as it is necessary to make decisions, e.g., to establish rules to control the right of way, both for vehicles and pedestrians. Thus, it is necessary to establish new rules of priority between approaches to the intersection to allow crossing or prohibiting movement at the intersection, which could lead to accidents (CASTRO; HIRAKAWA; MARTINI, 2017), (OVIEDO-TRESPALACIOS et al., 2017).

Synchronization of traffic signals minimizes traffic congestion, fuel consumption, and pollutant emissions. Also, it allows better traffic flow by combining green signal times, i.e., green waves for a series of intersections. These green waves provide the maximum number of vehicles passing, reduces stops, and delay for motorists at intersections (ADACHER; TIRIOLO, 2016), (MA; HE, 2019).

At an intersection between two or more roads, some movements cannot be performed simultaneously, as they conflict with each other. The control of an intersection is built from the synchronization of traffic signals which are controlled through infrastructure software systems and ICTs. This union between systems and ICTs has an advanced monitoring and performance capacity and consequently maintains the safety and coordination of all vehicles and pedestrians at intersections (NING; ZHANG; REMIAS, 2019).

These software systems present high complexity due to multiple crossings, various traffic scenarios and events, e.g., weather conditions, day of the week, time of the year, road works and accidents, as well as traffic flow data, deciding which phases of traffic should be approved at a given time (priority times), phase cycles (red, yellow and green), synchronization of crossings among others (LI; LV; WANG, 2016), (QADRI; GÖKÇE; ÖNER, 2020), (EOM; KIM, 2020).

It is worth noting that the structure of urban space is not static, that is, with the continuous improvement of the theory and practice related to urban management and operations, the urban components and their systems can be optimized and dynamically adjusted to better cover all areas of the city. At the same time, this structure can be changed according to the data that will realize the self-optimization of an urban space (MA et al., 2018).

1.2 Main and Specific Objectives

The main objective of this dissertation is to characterize a SysML profile to model the application needs and specific elements related to smart cities. The focus of this study is to propose an extension of SysML, that is, a profile that makes the needs of applications and elements closer to the domain of application modeling, both in design and in software architecture.

To achieve the general objective, the following specific objectives have been established:

1. Enhance SysML to characterize specific elements of smart cities. This specific objective is addressed in Chapter 3 and Chapter 4;

2. Modeling an urban traffic control system using the SmartCitySysML profile. This specific objective is addressed in Chapter 5;

3. Verify good properties of the structured model for an urban traffic control system using Timed Coloured Petri Nets (TCPN). This specific objective is addressed in Chapter 5.

1.3 Methodology

In order to achieve the proposed objectives, this dissertation has applied literature review and case study as research tools. The searches were performed in ACM, IEEEXplore, Springer, Scopus, and Science Direct digital bases restricted to the English language. In this research, no time range has been defined. Through these reviews, it is possible to discover the needs of the applications and the elements of a city, for example, stakeholders, requirements, solutions, processes, and dimensions.

To better identify these needs of the applications and elements of a smart city, a SysML extension has been proposed, i.e., a profile with more specific terms of smart cities. This SysML profile is named SmartCitySysML, and with this profile, it is possible to make the needs of applications and elements closer to the domain of application modeling, both in design and in software architecture.

The SmartCitySysML profile enables the use of common elements, found in smart city infrastructures, as native elements to be used to build systems' models. The SmartCitySysML includes elements of smart cities as native components of SysML, adapting the language to represent elements related to smart cities. The chosen SysML diagrams to be extended are Sequence diagram (SD), Requirements diagram (REQ), Block Definition diagram (BDD), and Internal Block diagram (IBD). These SysML diagrams were chosen to design a model of an urban traffic signal control system.

The case study details an application of the SmartCitySysML profile, i.e., a model of an urban traffic signal control system. Traffic signals are the most basic elements for controlling traffic in a city. Traffic signals and sensors are useful to control and manage the traffic flow of vehicles and pedestrians, as well as the starting point for data acquisition, for example, vehicle and pedestrian counting, traffic speed, congestion, and accident reports. Traffic signal control is a major and challenging problem in the real world, as traffic signals can provide potential solutions to ensure improved and efficient transport, energy consumption, and environmental protection (AN et al., 2017), (WEI et al., 2019).

The verification of system models can be performed by combining modeling languages, for example, UML and SysML with Petri Net to prove the functionality, integrity, consistency, and correctness of models, as the modeling provides information on the properties of systems before implementation. Another existing factor is that Petri Net, in general, are adequate to analyze and model the behavioral aspects of systems at different levels of abstraction. It is worth noting that Petri Net is not able to replace other modeling languages, for example, UML and SysML (KRISTENSEN; JØRGENSEN; JENSEN, 2004), (BARESI et al., 2015), (KRESOJA et al., 2016).

To model the basic architectural elements of the case study, Petri Net sub-models were developed. These Petri Net sub-models are applied to describe the behavior of each element of an urban traffic system, i.e., sensor, controller, and actuator. To formally model and verify the properties of the case study a Timed Coloured Petri Nets (TCPN) model is developed. This TCPN model is used to model the behavior of traffic signals and describe the properties of Petri Net from the TCPN model simulation. The analyzed behavioral properties were reachability, reversibility and home state, fairness, liveness, and boundedness.

In summary, this dissertation is based on the following script:

- Collect relevant studies on the main themes of this research: smart cities, SysML, and Petri Net are addressed in Chapter 2;
- Extension and Adaptation of SysML to characterize the specific elements of smart cities, addressed in Chapter 3;
- Design of a model for an urban traffic control system based on SmartCitySysML profile, addressed in Chapter 4;
- Design of Petri Net sub-models of the basic architectural elements of an urban traffic control system, addressed in Chapter 5;
- Verification of good properties of the model proposed for urban traffic control system from TCPN, addressed in Chapter 5.

1.4 Document Structure

This dissertation contributes to the research and practice in Software Engineering, especially to the sub-area of Software Architecture. An extension of the SysML profile for smart cities, named SmartCitySysML is proposed and fully described. A case study is also prepared for the urban traffic control system using the SmartCitySysML profile. Also, the behavioral properties of the case study were analyzed using the design and simulation of a TCPN model.

This dissertation is organized into 6 chapters. A brief description of the content of each chapter is presented below.

Chapter 2 - Background

The main idea is to present a background of the proposed research describing the concepts of Smart Cities, SysML, Timed Coloured Petri Nets, System Behavioral Properties, and Related Works.

Chapter 3 - SmartCitySysML: A SysML profile for Smart Cities Applications

The main idea is to describe the SysML profile, named SmartCitySysML, for modeling smart city applications to specify common elements of a city as native system design elements. In addition, a brief description of the elements of smart cities organized in the SmartCitySysML profile, e.g., Stakeholders, Requirements, Processes, Solutions, and Dimensions is presented.

This chapter is based on the article *"SmartCitySysML: A SysML Profile for SmartCities Applications"* (SOUZA; MISRA; SOARES, 2020) published in *The 20th International Conference on Computational Science and Its Applications* (ICCSA 2020), classified by CAPES as *Qualis* A3.

Chapter 4 - Design of Smart Cities Dimensions using a SmartCitySysML Profile

The main idea is to describe the extension of the SmartCitySysML profile to model dimensions of smart cities, e.g., people, economy, governance, environment, mobility, and living as native elements of system design. The profile extension has been expanded from the SysML Internal Block diagram (IBD).

This chapter is based on the article *"Design of Smart Cities Dimensions using a SmartCitySysML Profile"* published in *The 21st International Conference on Computational Science and its Applications* (ICCSA 2021), classified by CAPES as *Qualis* A3.

Chapter 5 - Design of Smart Cities Application with SmartCitySysML: A Case on Urban Traffic Signal Control

The main idea is to detail an application of the SmartCitySysML profile to model an urban traffic signal control system presenting the user requirements and the Sequence diagram (SD), Block Definition diagram (BDD), and Requirements diagram (REQ). Petri Net sub-models were also designed to separately model the behavior of the basic architectural elements of this model. The formal model and verification of this model are performed using Timed Coloured Petri Nets (TCPN) to simulate and verify the model, i.e., prove properties such as reachability, reversibility and home state, fairness, liveness, and boundedness.

This chapter is based on the articles:

- *"Combining SysML with Petri Nets for the Design of an Urban Traffic Signal Control"* published in *The 21st International Conference on Computational Science and its Applications* (ICCSA 2021), classified by CAPES as *Qualis* A3.

- *"Combining SysML and Timed Coloured Petri Nets for Designing Smart City Applications"* submitted to *Systems Engineering*, classified by CAPES as *Qualis* A4.

Chapter 6 - Conclusion

The main idea is to present the conclusions of this dissertation, the limitations and challenges of the research, the works submitted, the threats to validity, the related published works, and some possibilities for future works that can be performed to continue this research.

2

Background

This chapter describes fundamental concepts related to Smart Cities, SysML, Timed Coloured Petri Nets (TCPN), and System Behavioral Properties. In Section 2.1 definitions regarding smart cities are presented. The SysML language is discussed in Section 2.2. Section 2.3 presents the TCPN language. Section 2.4 presents the behavioral properties of the systems. Section 2.5 presents the related work.

2.1 Smart Cities

The term Smart Cities contains a variety of synonyms, which can often be replaced by “intelligent city”, “digital city”, "virtual city", "wired city", "learning city", "green city", "sustainable city", "information city", "ubiquitous city" or "knowledge city" (ALBINO; BERARDI; DANGELICO, 2015).

The term smart city was first used in the 1990s meaning the use of Information and Communication Technologies (ICT) appropriately, and consequently, to promote better infrastructures for cities (SAHOO; RATH, 2017). In addition, urban challenges stimulated the search for better quality services, therefore, they encouraged cities to find a way to integrate technology in all aspects of the urban environment to offer their citizens better quality of life (BIFULCO et al., 2016).

A city can be described as a smart city when the social, environmental, and economic development factor is balanced and linked through decentralized processes to efficiently manage the main assets and resources of urban flows for real-time (ISMAGILOVA et al., 2020).

Cities become smart when they make use of ICT to integrate and synthesize data for some purpose, for example, ways to improve efficiency, equity, sustainability, and quality of life in cities (BIBRI; KROGSTIE, 2017). In this way, adapting and evolving a city to new processes and applications is a strategy adopted to mitigate the problems generated by urban population growth and rapid urbanization, e.g., air pollution, resource scarcity, waste management, inadequate infrastructure due to deterioration, and/or aging, health concerns, and traffic congestion (CHOURABI et al., 2012).

According to Duarte, Oliveira and Bernardino (DUARTE; OLIVEIRA; BERNARDINO, 2015) and Bolívar and López-Quiles (BOLÍVAR; LØPEZ-QUILES, 2018), smart city refers to the search and identification of intelligent solutions that enable modern cities to improve the quality of services provided to citizens through creativity, innovation, and decision making quickly and efficiently, as well as economic growth.

Piro et al. (PIRO et al., 2014) state that a smart city is intended as an urban environment that, supported by pervasive ICT systems, can offer advanced and innovative services to citizens to improve the overall quality of their daily life. Four common characteristics of smart cities are presented in (ALBINO; BERARDI; DANGELICO, 2015):

1. The network infrastructure that allows for efficiency in cultural development, political and social management;
2. Emphasis on urban development led by companies and creative activities to promote urban growth;
3. Social inclusion of urban citizens and social capital for urban development;
4. Environment as a strategic component for the future.

Shahidehpour and Li and Ganji (SHAHIDEHPOUR; LI; GANJI, 2018) assert smart city is a safe, efficient, and environmentally friendly urban center with infrastructure designed, built, and maintained through technology. In this way, products and services designed for smart cities provide solutions to efficiently improve the management of modern cities. These solutions gather data from citizens' daily lives, including their activities, preferences, and habits (ALCÓN et al., 2016).

Smart cities have become complex ecosystems with the potential to improve urban habitability, feasibility, and sustainability through a network of people, processes, and data favoring products and technological solutions for end-users. Also, these cities develop smart initiatives concerning creativity, innovation, high quality of life, economic growth, be safe and protected, and be socially, economically and environmentally sustainable (KIM; RAMOS; MOHAMMED, 2017), (ISMAGILOVA et al., 2020).

In general, smart cities are portrayed as the association of several connected networks, that is, an integrated and multidimensional system that provides and gathers continuous data on the movements of people and materials on a city (BIBRI; KROGSTIE, 2017), (FERNANDEZ-ANEZ; FERNÁNDEZ-GÜELL; GIFFINGER, 2018).

Several cities around the world have used the concept of smart cities and/or developed infrastructures to acquire this new status and/or found strategies to adapt their services, processes, and applications. Rio de Janeiro, Curitiba, London, New York, Paris, Amsterdam, Reykjavik, Tokyo, Busan, Dubai, Stockholm, and Santander are examples of cities that are becoming smart cities (KIM; RAMOS; MOHAMMED, 2017), (SOLANO; CASADO; UREBA, 2017), (GHARAIBEH et al., 2017), (MACKE et al., 2018), (AKANDE et al., 2019), (ISMAGILOVA et al., 2020).

Batty et al. (BATTY et al., 2012) declare that smart cities are often pictured as constellations of instruments across many scales that are connected through multiple networks. These networks provide continuous data regarding the movements of people and materials in terms of the flow of decisions about the physical and social form of the city. Cities, however, can only be smart if there are intelligent functions that can integrate and synthesize these data to some purpose, e.g., ways of improving the equity, efficiency, sustainability, and quality of life in cities (BIBRI, 2019).

Silva et al. (SILVA et al., 2019) argue that smart cities are cities with computerized software-intensive systems composed of processes sensitive to the context of Big Data, cloud networks, and standalone communication across multiple distributed devices. These processes are used in a more efficient urban planning paradigm through predictions, which allow decision making before problems and/or emergencies occur, as well as making urban activities more economic and sustainable.

Giffinger et al. (GIFFINGER; GUDRUN, 2010) state that a smart city has six dimensions for urban development with awareness and participation of citizens of a city. These dimensions are the smart economy, smart people, smart governance, smart mobility, smart environment, and smart living. Cohen (COHEN, 2012), Staffans and Horelli (STAFFANS; HORELLI, 2014) and Moustaka et al. (MOUSTAKA et al., 2018) also declared the same dimensions, but with different factors and/or characteristics for smart cities.

2.2 SysML

SysML (OMG, 2019) has been developed by the Object Management Group (OMG) and International Council on Systems Engineering (INCOSE) to a unified language for general-purpose modeling for systems engineering applications. SysML is a UML profile applied to systems that include hardware, software, information, processes, people, and procedures.

SysML reuses parts of UML and additionally offers new language elements, such as value types, type of quantity, and the opportunity to describe the functionality of systems. Therefore, it allows one to model a wide variety of systems from different perspectives (WOLNY et al., 2020). Current version of SysML, named SysML 1.6, was released on December 2019 (OMG, 2019).

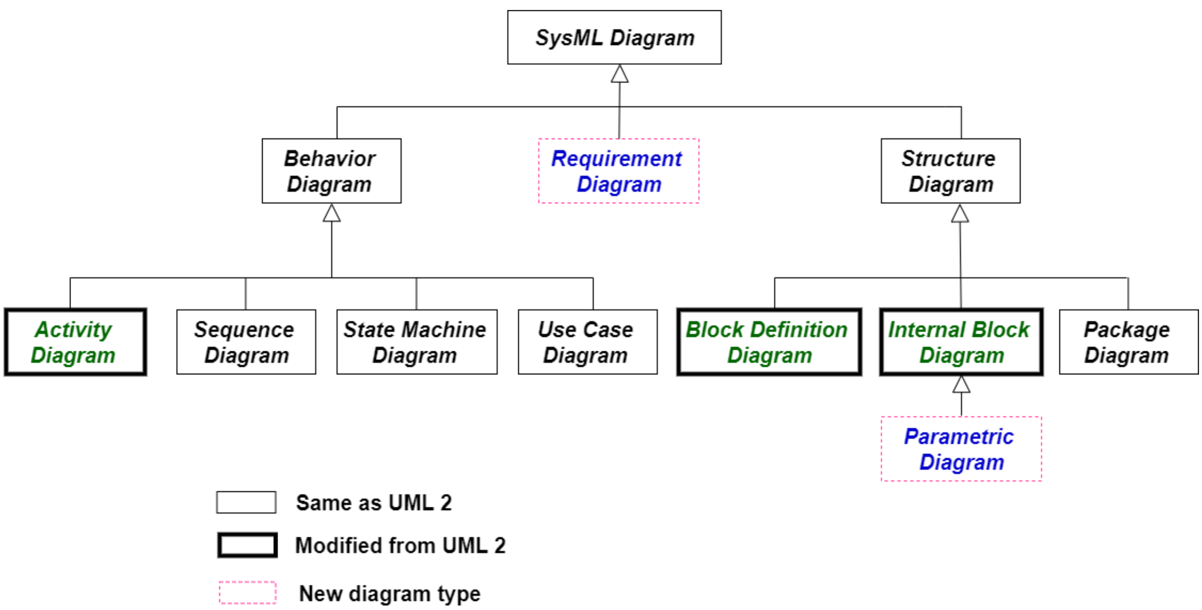
SysML has a focus on Systems Engineering, different from UML, which is a software engineering modeling language. Therefore, some UML diagrams and elements are used in SysML from the systems point of view, and software elements such as classes and objects are not present in SysML (FRIEDENTHAL; MOORE; STEINER, 2014).

SysML can be combined with UML, and the requirements constructs provided by SysML fill the gap between user requirements specification, which are most often written in natural language, and Use Case diagram, used as an initial specification of scenarios of system requirements (OMG, 2019).

It is worth mentioning that SysML also allows modeling in multiple architectural views, through diagrams that can model the structure, behavior, and requirements of a system. In this way, SysML is characterized through diagrams, models, structural and behavioral elements, effective in specifying requirements, allocations, and restrictions on system properties to support a systems engineering project (FRIEDENTHAL; MOORE; STEINER, 2014), (BIGGS; SAKAMOTO; KOTOKU, 2016).

Sequence, State Machine, Use Cases, and Package diagrams have not been changed from UML 2.0, except that their focus is broader, regarding software as well as systems elements. Block Definition, Activity, and Internal Block diagrams have been modified from UML, and the Requirements and Parametric diagrams are new (OMG, 2019). The taxonomy of SysML diagrams is shown in Figure 1. SysML diagrams used in this dissertation are briefly presented below. A full description of all SysML diagrams can be found in (OMG, 2019).

Figure 1 – SysML Diagram Taxonomy.



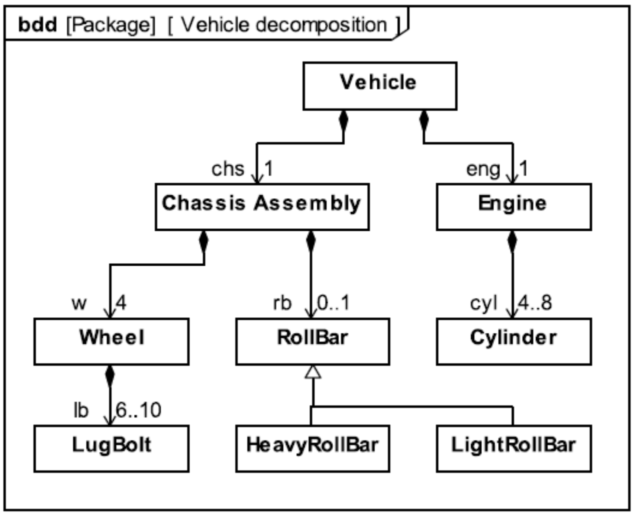
Source: OMG (OMG, 2019)

Blocks are modular units of the system description. Each block defines a collection of features to describe a system or other element of interest. These may include both structural and behavioral features, such as properties and operations, to represent the state of the system and behavior that the system may exhibit (OMG, 2019).

Block Definition diagram (BDD)

SysML Block Definition diagram (BDD) is a diagram that shows the system components, their contents (properties, behaviors, constraints), interfaces, and relationships. The Block Definition diagram (BDD) in SysML defines block characteristics and relationships between blocks, such as associations, generalizations, and dependencies. In this way, it captures the definition of blocks in terms of properties and operations, and relationships, such as a system hierarchy or a system classification tree (OMG, 2019). It is worth noting that the Block Definition diagram (BDD) is based on the UML class diagram, with constraints and extensions. Figure 2 shows an example of decomposition for the vehicle in a SysML Block Definition diagram (BDD).

Figure 2 – Decomposition for Vehicle in a SysML Block Definition diagram.

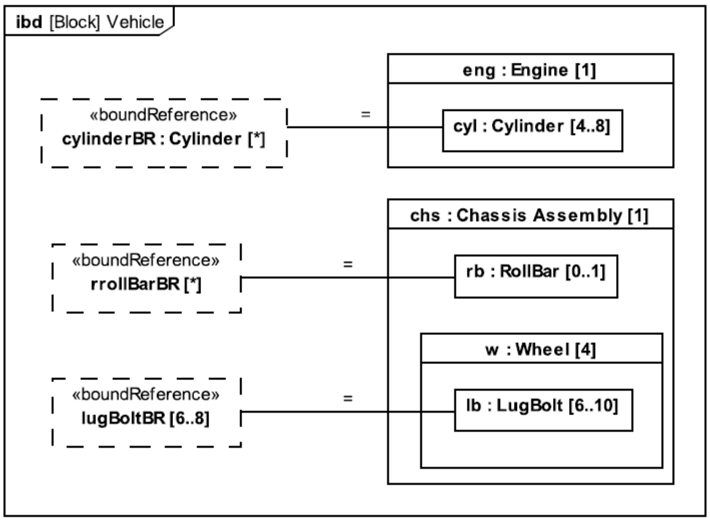


Source: OMG Systems Modeling Language Version 1.6 (OMG, 2019)

Internal Block diagram (IBD)

SysML Internal Block diagram (IBD) is a diagram about a specific block that shows its encapsulated structural content, i.e., parts, properties, connectors, ports, and interfaces. In this way, the SysML Internal Block diagram (IBD) captures the internal structure of a block in terms of properties and connectors between properties. In this case, a block can include elements, properties, values, parts, and references to other blocks (OMG, 2019). It is worth noting that the SysML Internal Block diagram (IBD) is based on the UML composite structure diagram, with constraints and extensions as defined by SysML. Figure 3 shows the same decomposition as Figure 2 into a SysML Internal Block diagram (IBD) that includes bound references.

Figure 3 – Decomposition for Vehicles in a SysML Internal Block diagram.



Source: OMG Systems Modeling Language Version 1.6 (OMG, 2019)

Sequence diagram (SD)

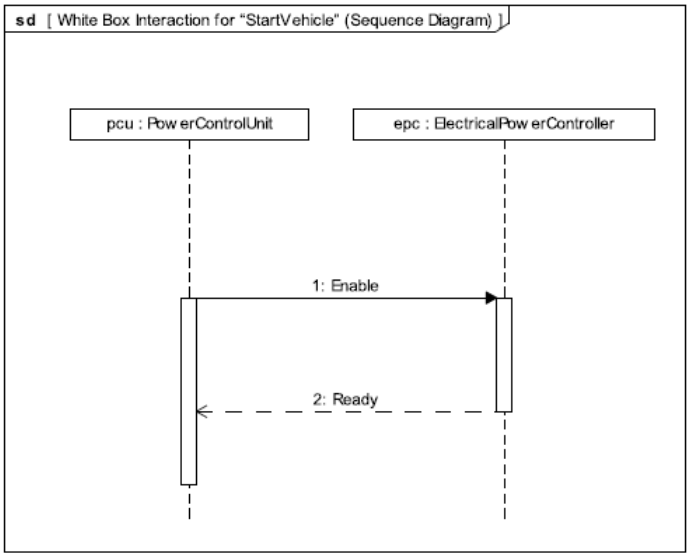
The SysML Sequence diagram (SD) describes the flow of control between actors and systems (blocks) or between parts of a system. This diagram represents the sending and receiving of messages between the interacting entities called lifelines, where time is represented along the vertical axis. The Sequence diagram (SD) can represent highly complex interactions with special constructs to represent various types of control logic, reference interactions on other Sequence diagram (SD), and the decomposition of lifelines into their constituent parts (OMG, 2019). Figure 4 shows an example of the breakdown of a vehicle's energy system for starting.

Requirements diagram (REQ)

SysML Requirements diagram (REQ) is a diagram that shows the relationships between requirements constructs, model elements that satisfy them, and test cases that verify them. In this way, the SysML Requirements diagram (REQ) specifies the functional and non-functional requirements within models so that they can be traced to other model elements (OMG, 2019). Figure 5 shows the relationships of the requirements for the acceleration of a vehicle.

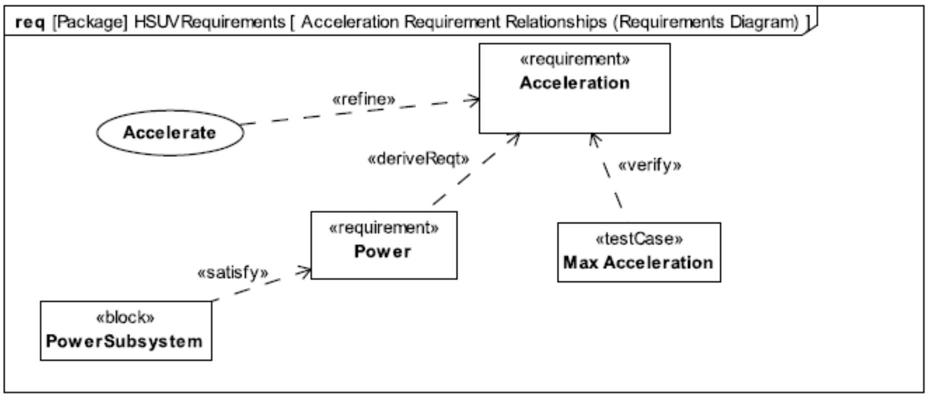
Each SysML Requirements is represented individually with ID and Name attributes, but

Figure 4 – Decomposition of a Vehicle's Starting Power System into a SysML Sequence diagram.



Source: OMG Systems Modeling Language Version 1.6 (OMG, 2019)

Figure 5 – Relationships of the requirements for vehicle acceleration in a SysML Requirements diagram.



Source: OMG Systems Modeling Language Version 1.6 (OMG, 2019)

additional attributes can be considered by expanding the basic SysML Requirement model. The SysML Requirements diagram (REQ) represents relationships between requirements, through the hierarchy of relationships, derive, master, satisfy, verify, refine, and trace (OMG, 2019). Therefore, SysML Requirements diagram (REQ) is a useful way to organize requirements by showing the types of relationships between each requirement. Another characteristic of using the SysML Requirements diagram (REQ) is to standardize the way of specifying requirements through a defined semantics (SOARES; VRANCKEN; VERBRAECK, 2011).

2.3 Timed Coloured Petri Nets

Petri Net is a graphical formal method applicable to a large variety of systems providing important information about the structure and behavior of the modeled systems, i.e., simultaneity, concurrency, dynamic behavior, synchronous and asynchronous communication, and resource sharing have to be modeled (PETRI, 1962), (PETERSON, 1977), (REISIG, 1985), (MURATA, 1989).

Petri Net is formally defined (MURATA, 1989), as a tuple:

$$P = (P, T, F, W, M_0), \text{ where}$$

$$P = \{p_1, p_2, ..., p_3\} \quad \text{is a finite set of places;}$$

$$T = \{t_1, t_2, ..., t_3\} \quad \text{is a finite set of transitions;}$$

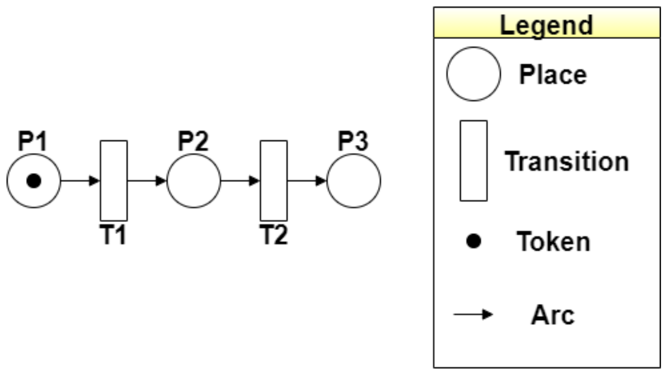
$$F \subseteq (P\text{x}T) \cup (T\text{x}P) \quad \text{is a set of arcs;}$$

$$W : F \longrightarrow \{1, 2, 3, ...\} \quad \text{is a function of weights;}$$

$$M_0 : P \longrightarrow \{1, 2, 3, ...\} \quad \text{is the initial marking,} \quad P \cap T = \varnothing \quad \text{e} \quad P \cup T \neq \varnothing;$$

According to Peterson (PETERSON, 1977), the graphic structure of a Petri Net is a bipartite directed graph composed of four elements, explained briefly below and shown in Fig. 6.

Figure 6 – Elements of Petri Net.



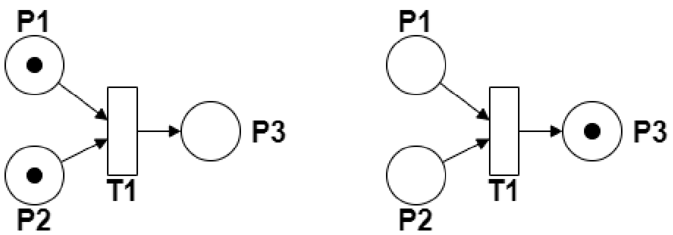
Source: the author

- *Places* can represent, for example, conditions, status, states or operations;
- *Transitions* can represent, for example, start or stop events, which occurs to change the status of places;

- *Arcs* represent connections between places and transitions;
- *Tokens* can represent the number of elements or the current availability of resources.

An execution example is shown in Fig. 7. Initially, places P1 and P2 with one token are enabling transition T1. After the firing of transition T1, the tokens in P1 and P2 are removed, and one token is deposited in place P3.

Figure 7 – Execution of a Petri Net.



Source: the author

Coloured Petri Nets (CPNs) (JENSEN, 1992), (JENSEN, 1994), (JENSEN, 1997), (KRISTENSEN; CHRISTENSEN; JENSEN, 1998), an extension of Petri Net, are a graphical language for constructing models of concurrent systems and analysing their properties. CPN is a discrete-event modeling language combining Petri Net and the functional programming language CPN ML which is based on Standard ML. CPN and Petri Net are applicable more generally for modeling systems where concurrency and communication are key characteristics.

Coloured Petri Nets (CPNs) are formally defined (JENSEN, 1995) as a tuple:

$$P = (\sum, P, T, A, V, C, G, E, I), \text{ where}$$

$$\sum : \text{is a set of colour sets;}$$

$$P : \text{is a set of places;}$$

$$T : \text{is a set of transitions;}$$

$$A : \text{is a set of arcs;}$$

$$V : \text{is a set of variables;}$$

$$C : \text{is the colour set function (assigns colour sets to places);}$$

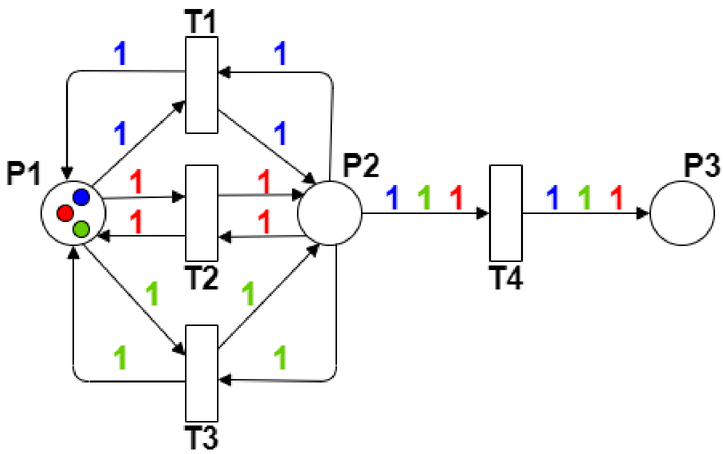
$$G : \text{is the guard function (assigns guards to transitions);}$$

$$E : \text{is the arc expression function (assigns arc expressions to arcs);}$$

$$I : \text{is the initialisation function (assigns initial markings to places).}$$

An example of CPN is shown in Fig. 8. Initially, place P1 has three tokens (blue, red, and green) and is enabling transitions T1, T2, and T3. Transitions T1, T2, and T3 only allow one direction to be enabled at a time. After transitions T1, T2 and T3 are triggered, tokens in P1 are removed and deposited in place P2. Transition T4 does not ask for any other three tokens, but a blue token, a red token, and a green token, and these three tokens (blue, red, and green) are deposited in place P3. It is worth noting that from one place to a transition only one token at a time is allowed.

Figure 8 – Example of a CPN.



Source: the author

One of the extensions of CPN is the Timed Coloured Petri Nets (TCPN). A TCPN model allows one to investigate performance measures, such as queue lengths and waiting times. The main difference between TCPN and CPN models is that the tokens in a TCPN model, in addition to the token color, can present data time (seconds). This means that marking a place where tokens carry data value is now a timed multiset specifying the elements in the multiset along with their number of appearances and their timestamps (JENSEN; KRISTENSEN; WELLS, 2007).

TCPNs are a discrete event modeling language that combines the resources of Petri Net with the resources of a high-level programming language. TCPN provides the basis for graphical notation and basic primitives to model, simultaneously, communication and synchronization, as well as can be applied for simulation-based performance analysis, investigating performance measures such as delays, throughput, and queue lengths in the system, and for modeling and real-time system validation (JENSEN, 1987).

2.4 System Behavioral Properties

An important feature of Petri Net is the possibility of verifying the correctness of the designed model, i.e., to prove the presence or absence of properties. Petri Net properties' can be divided into behavioral, which depends on the initial marking, and structural, which does not depend on the initial marking because they are defined from the network structure. Examples of behavioral properties are reachability, boundedness, liveness, reversibility and home state, fairness, safeness, coverability, and persistence. Examples of structural properties are structural controllability, structural boundedness, conservativeness, repetitiveness, and consistency (MURATA, 1989).

In this research, only the behavioral properties are chosen for the reason that represents the dynamics of the Petri Net, and consequently, allow the analysis of various features and problems associated with the system modeled by Petri Net. The behavioral properties are described below as follows (MURATA, 1989):

- *Reachability*: fundamental basis for studying the dynamic properties of any system. The firing of an enabled transition will change the token distribution (marking) in a net according to the transition rule. A sequence of firings will result in a sequence of markings. A marking M_n is said to be reachable from a marking M_0 if there exists a sequence of firings that transforms M_0 to M_n. The set of all possible markings reachable from M_0 in a Petri Net N is denoted by $R(N, M_0)$. The reachability problem for Petri Net is the problem of finding if $M_n \in R(N, M_0)$ for a given initial marking M_0 in a Petri Net.

- *Boundedness*: a Petri Net is k-bounded if the number of tokens in each place does not exceed a finite number k for any marking reachable from M_0, i.e., $M(p) \leq k$ for every place p and every marking M $\in R(N,M_0)$.

- *Liveness*: a Petri Net is live if, no matter what marking has been reached from the initial marking, it is possible to fire any other transition of the net by progressing through some further firing sequence.

- *Reversibility and Home State*: it is said that a Petri Net is reversible if, from any marking, it is always possible to return to the initial marking.

- *Fairness*: for a given initial marking two transitions in a Petri Net are said to be in a B-fair relation if the number of times that either can fire before the other fires are bounded. Two transitions are in a structural B-fair relation (SF-relation) if they are in a B-fair relation for any initial marking.

- *Safeness*: it can be determined for both individual places and the entire net. A place is said to be safe if, for all possible makings, the number of tokens in that place never exceeds one. A Petri Net are declared safe if all the places in the net are safe.

- *Coverability*: a marking M in a Petri Net (N, M0) is said to be coverable if there exists a marking M' in the reachability set of M0 such that M'(p) ≥ M(p) for each p in the net.

- *Persistence*: a Petri Net is said to be persistent if, for any two enabled transitions, the firing of one cannot disable the other.

2.5 Related Works

This section presents works related to smart cities, focusing on using UML or SysML and profiles for smart cities that model the problems, the needs of the applications, and the elements of a city from a computational point of view, such as the formal verification of system models for smart cities with Timed Coloured Petri Nets (TCPN).

Apvrille et al. (APVRILLE; SAQUI-SANNES; KHENDEK, 2006) proposed the TURTLE-P profile, which enables modeling of distributed and critical systems using UML Components diagram and Class diagram, Activity diagram, Component diagram, and Deployment diagram. TURTLE-P addresses concrete descriptions of communication architectures, including quality-of-service parameters (delay, jitter, and others), verification of properties and constraints, as well as formal validation of critical software applications based on captured and validated user requirements in terms of scenarios. TURTLE-P extended two UML diagrams, the Class diagram for architectural description and the Activity diagram to describe behaviors, and used the Component diagram and Deployment diagram for low-level design elaboration. To illustrate the use of TURTLE-P, the authors applied this profile to the modeling and validation of a space-based telecommunications system (satellites and probes) using for modeling the Class diagram to identify the classes responsible for sending and receiving the allocation reports, the Activity diagram to model the synchronization behavior of the operations used in the system, the Component diagram for the low-level design of the system, and the Deployment diagram to realize the connection between the satellites and the probe. For validation of TURTLE-P, the authors analyzed the reachability graph, increased the abstraction of the system at the Class diagram level, and decreased the abstraction of the system at the Deployment diagram level. For validation of the properties, the authors used the analyses modeled with TURTLE-P classes that are distinct from the system tasks, so the system architecture remains unchanged.

Jamro et al. (JAMRO; RZONCA; RZąSA, 2015) used the SysML Block Definition diagram (BDD), SysML Sequence diagram (SD), and SysML Internal Block diagram (IBD) to specify and test communication tasks of distributed control systems (DCSs) composed of a controller and two input/output modules. The structure and configuration of communication tasks in DCSs are modeled from the SysML Block Definition diagram (BDD) to indicate the number of communication tasks and specify their parameters (function, address, priority, and timeout), the SysML Sequence diagram (SD) to separate the model of each communication task, and the SysML Internal Block diagram (IBD) to assign the communication tasks with the specific connections between the controller and the two input/output modules. From these SysML diagrams, a model for a communication subsystem was implemented in Java, i.e., the model of a master controller cycle. Then a TCPN model was automatically generated to estimate the performance of the implementation and predict the behavior in various cases. The authors state that the simulation results can be analyzed using the R statistical package, as indicate that the model is reliable and can be used to draw reliable conclusions.

Salem et al. (SALEM et al., 2016) propose a new UML profile, R-UML, to model, verify, and manage the structure and behavior of control systems that share adaptive resources. Initially, the authors illustrate an example of running an adaptive discrete event system consisting of two tasks that share two resources and then reconfigure by adding a new resource to the two existing tasks. In the proposed profile, R-UML, the UML Class diagram is used to model the different shared resources and their rules, and the UML State Machine diagram is used to represent the behavior of the system tasks. Then, these models were transformed into Timed Petri Net models to solve the problem of simultaneous access of the adaptive shared resources, as well as automatically verify the good properties of the models, such as security and deadlock.

Incki and Ari (INCKI; ARI, 2018) represent through a UML profile extension, a model of a system for smart parking in smart cities. Their goal is to describe the expected and/or faulty behavior of sensors in a smart parking system employing UML Sequence diagrams, and for model verification, the authors used runtime and interaction patterns to examine the performance of the parking system with IoT devices, i.e., sensors for smart cities.

Songwiroj et al. (SONGWIROJ; VATANAWOOD; VANIT-ANUNCHAI, 2018) suggest an alternative to model the railway network from TCPN building blocks. The authors used two types of building blocks, the first is a railway station that can support up to double tracks in each direction, and the second represents only a single track. The model of the railway network was developed at a high abstract level using the two building blocks. This model was transformed into multiple TCPN models to overlay the transition of each connected block to make a single TCPN model and represent the location of the physical parts of the rail network. The latter generated model was verified using CPN Tools to ensure the correctness, safety, and liveness of the formal railway network model.

Wu and Zheng (WU; ZHENG, 2018) suggest a formal model-based approach for quantitative safety analysis of railway domain using TCPN. This approach contributes as a modeling method through TCPN, e.g., state-space based methods through state space reporting and methods for evaluating the safety characteristics of the meantime to hazardous events and the probabilities of staying in normal and safe states based on the data collected during the model simulation of a railroad grade crossing control system. According to the authors, with this proposal, it is possible to estimate the reliability and safety of a system without building event chain-based models (fault trees and event trees).

Mahmoudi-Nasr (MAHMOUDI-NASR, 2019) proposes a TCPN model to address and predict internal and/or external threats in supervisory control and data acquisition (SCADA) and uses UML Use Case diagram and UML Sequence diagram to represent alarm handling (AH) transactions. According to the authors, the proposed alarm handling model does not refer to a specific critical infrastructure (CI) application and is based on a general approach that alarm transactions are integrated with commands from the dispatcher and substation/maintenance operator. To demonstrate the potential of the alarm, the authors used a real case study in a power system simulating some scenarios with a different number of substations and the error rates were analyzed even under internal and/or external threat conditions.

Elidrissi et al. (ELIDRISSI et al., 2019) used Timed Synchronized Petri Nets (TSPN) as a dynamic control strategy of an urban intersection to model separately and control each movement at the intersection. According to the authors, this strategy allows managing conflicts between the phases, reducing the length of the queue, and ensuring more security. Each isolated intersection is considered as a discrete event system and modeled by Petri Net. To verify the system, the chosen properties were accessibility, delimitation, safety, and liveliness.

Díaz et al. (DÍAZ et al., 2020) present a model for urban traffic control considering air pollution and some traffic problems. To do so, the authors used Complex Event Processing technology (CEP) to process the information collected from sensors and determine traffic levels, and Coloured Petri Nets (CPN) to model a map of the city with some connections that can be closed due to air quality or traffic conditions, i.e., to obtain ideal routes. In the city, space state analysis maps were also made through simulation. Also, the CPN city map model is applied to a real scenario, which is based on the division into districts of Madrid.

Kotronis et al. (KOTRONIS et al., 2020) proposed a domain-specific SysML profile that allows a definition and visual verification of Service Level (LoS) during system operation, through specific requirements and an association of these requirements with specific components of the Rail Transport System (RTS), as well as generating simulation models using Query/View/-Transformation (QVT), Meta-Object Facility (MOF) and Discrete Event System Specification (DEVS). According to the authors, LoS is focused on passenger comfort, and consequently, evaluates the performance, complexity, traceability, quality, operations of an RTS, and the costs associated with LoS.

Different from the works presented by Apvrille et al. (APVRILLE; SAQUI-SANNES; KHENDEK, 2006), Salem et al. (SALEM et al., 2016) and Kotronis et al. (KOTRONIS et al., 2020), this thesis includes SysML for systems engineering models and Petri Net models to verify the good behavioral properties of these models.

Similar to Jamro et al. (JAMRO; RZONCA; RZąSA, 2015), in this research SysML and Petri Net are integrated for software and systems modeling. However, their approach is more dedicated to source code generation and simulation, and this thesis has focus on formal verification of model properties.

This dissertation is comparable to the work of Incki and Ari (INCKI; ARI, 2018) for modeling the behavior of a system for smart cities. Díaz et al. (DÍAZ et al., 2020) elaborated a model with Coloured Petri Nets (CPN) for urban traffic control considering air pollution and some traffic problems, and this thesis elaborated a model with Petri Net for the architecture of an urban traffic control system considering the "green waves" in a region of high traffic flow in a city in northeastern Brazil.

Similar to Songwiroj et al. (SONGWIROJ; VATANAWOOD; VANIT-ANUNCHAI, 2018), Wu and Zheng (WU; ZHENG, 2018), Mahmoudi-Nasr (MAHMOUDI-NASR, 2019), Elidrissi et al. (ELIDRISSI et al., 2019), this dissertation also used Timed Coloured Petri Nets (TCPN) to model and formally verify the behavioral properties of a system.

3

SmartCitySysML: A SysML profile for Smart Cities Applications

In this research, SysML was chosen to create the profile for smart cities because it provides modeling in multiple architectural views, through diagrams that can model the structure, behavior, and requirements of the system. The creation of a SysML profile consists of a generic extension mechanism for SysML and is defined by elements such as stereotypes and constraints applied to certain modeling elements. Consequently, by bringing together all the definitions of these elements, it is possible to adapt SysML to a given platform or domain.

The development of this type of profile makes it easier to compose decisions based on better-described facts, encourages stakeholder involvement, promotes the exchange of experiences by analyzing the strengths and weaknesses of a city, engages in the needs of each dimension of a city, and uses smarter technologies and approaches to provide better services and quality of life for citizens. Therefore, a profile facilitates the use of common elements in the infrastructures of smart cities, assists the control of the infrastructures of these cities, and provides a visual representation from a practical point of view.

The development of a profile for smart cities arose from the challenges as well as the structuring and illustration of the characteristics and peculiarities of city elements. A specific profile for smart cities encourages stakeholder involvement as they can deal with their daily elements and language, promotes the exchange of experiences by analyzing the strengths and weaknesses of a city, and engages in the needs of each dimension of a city.

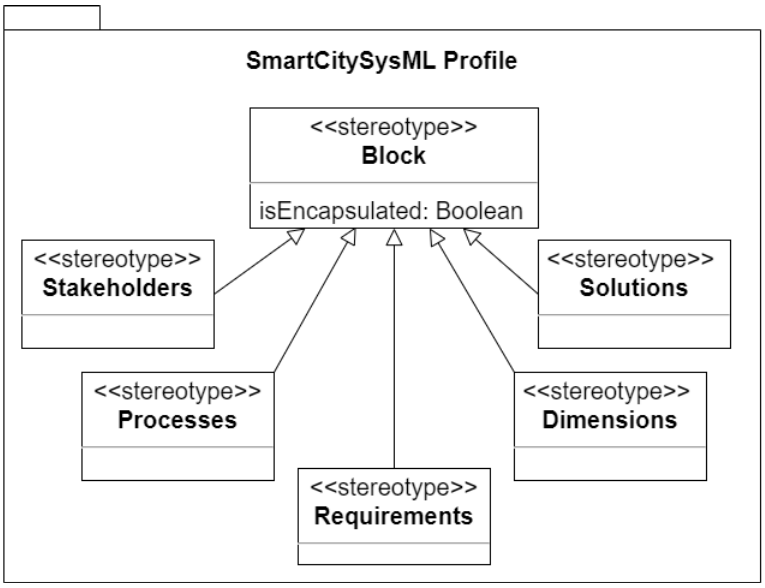
The SmartCitySysML profile can be used to meet the needs of management, operation, and decision making, as well as the basis for designing software solutions for smart cities through urban data modeling so that various information services are related and provided to different users. Thus, this profile allows the realization of a successful system and is a good option for the design of complex systems, for example, real-time systems that are used to control a city’s infrastructure.

The SmartCitySysML profile is extended from the SysML diagrams of Requirements diagram (REQ), Sequence diagram (SD), and Block Definition diagram (BDD) to model system elements and software for smart cities. As a result, SmartCitySysML facilitates the use of common elements in smart city infrastructures and provides a visual representation to evaluate quality of diagrams from a practical point of view.

Differences of SmartCitySysML profile compared to SysML are restricted to the introduction of new stereotypes (types), i.e., stakeholders, processes, requirements, solutions, and dimensions are represented as stereotypes of the SysML Block Definition diagram (BDD). Each new stereotype has new stereotypes, for example, the dimensions stereotype has the stereotypes economy, living, mobility, people, governance, and environment.

The SmartCitySysML profile is organized into 5 main elements, named Processes, Stakeholders, Requirements, Solutions, and Dimensions, which are explained as follows. Figure 9 illustrates the overview of the SmartCitySysML profile. This profile can be used for any smart city application.

Figure 9 – Overview of the SmartCitySysML Profile.

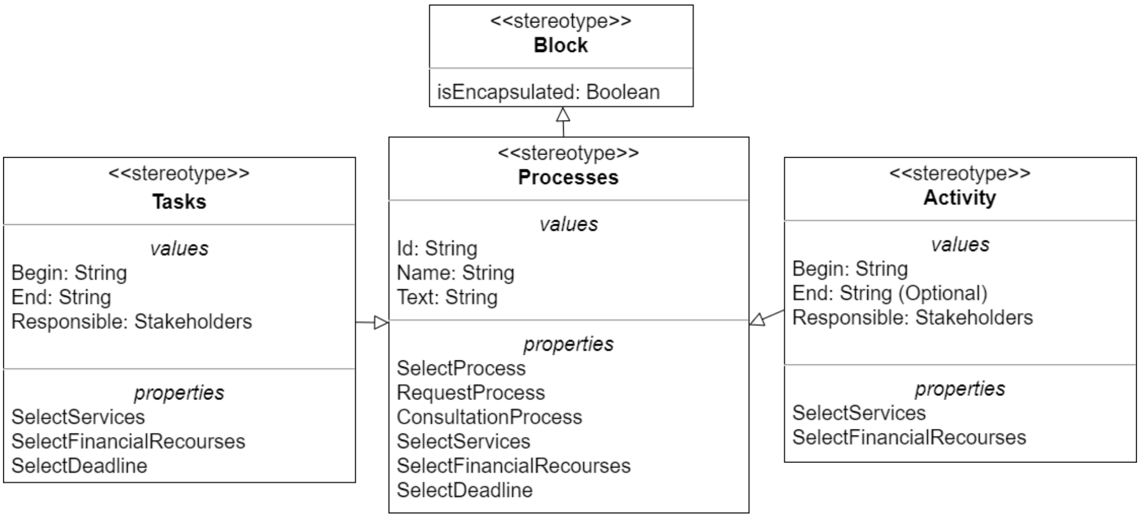


Source: the author

3.1 Processes

By definition, a Process is composed of tasks and activities involving a set of stakeholders (KINAWY; EL-DIRABY; KONOMI, 2018). In smart cities, processes are part of their development to support decision making and accelerate the deployment of effective and smart technologies and consequently provide cities with the opportunity to become safer and more inclusive, resilient, and sustainable (MORA; DEAKIN; REID, 2019). In SmartCitySysML the tasks and activities are proposed as shown in Fig. 10.

Figure 10 – Types of Processes.



Source: the author

Activities are more general than tasks, and also require more resources to be completed. Examples of tasks are managing taxes, organizing services, and developing social functions. Examples of activities are consulting and projects related to health, education, safety, transport, and others.

Activities in smart cities extract and record information, for example, for modeling applications, services, and systems (POURZOLFAGHAR; BASTIDAS; HELFERT, 2019). Tasks in smart cities are related to data collection, storage, analysis, system control, and user interaction (SHAHROUR et al., 2017).

Duan et al. (DUAN et al., 2018) compliment by stating that tasks play important roles in building a city safely, for example, obtaining the representation of resources for video analysis for facial recognition and/or identification of people and/or vehicles.

Both tasks and activities are considered essential for development of smart cities, as they are responsible for daily processes, for example, traffic control, air quality control, and health quality control, among others.

In smart cities, processes, i.e., tasks and activities are essential for decision making in all scenarios and dimensions in a balanced, effective, and efficient way using all available data and information, and their relationships to improve citizens' daily lives, as well as providing mechanisms to detect trends, predict events and/or situations, and identify tools to manage city services (D'ANIELLO; GAETA; ORCIUOLI, 2018).

Ardito et al. (ARDITO et al., 2019) assert that the various processes for decision making of smart cities are obtained, defined, and implemented from the creation and management of knowledge for the development of cities. The authors also complement that these processes can be modified according to the need to establish new processes.

Kumar et al. (KUMAR et al., 2020) declare that the processes of a smart city are complex, as they depend on the various stakeholders to plan and implement the decisions to define, design, and deliver services, to transform and improve a city.

3.2 Stakeholders

By definition, a Stakeholder is a person or group that can affect the organization and management behavior adopted in response to these groups and individuals (FROOMAN, 1999). Stakeholders contribute to city planning and development in a balanced way through innovative actions, engagement, and collaboration. For this, all stakeholders need to understand that their actions influence all scenarios and dimensions of a smart city (ALEXOPOULOS et al., 2019).

In a smart city, there are different stakeholder groups defined as citizens, city authorities, communities, academic institutions, research organizations, government institutions, local governments, and private companies, both locally and on a large scale (FERNANDEZ-ANEZ, 2016). It is worth noting that different stakeholders vary in their areas of expertise, objectives, and viewpoints (MARRONE; HAMMERLE, 2018).

Stakeholders in smart cities must be able to participate actively, make decisions, be integrated and participative, as well as have a widespread democratic character to predict future effects to ensure sustainable, conscious, interactive, and efficient development (WILLEMS; BERGH; VIAENE, 2017), (KÖK; ŞIMŞEK; ÖZDEMIR, 2017), (FERRARIS; BELYAEVA; BRESCIANI, 2018).

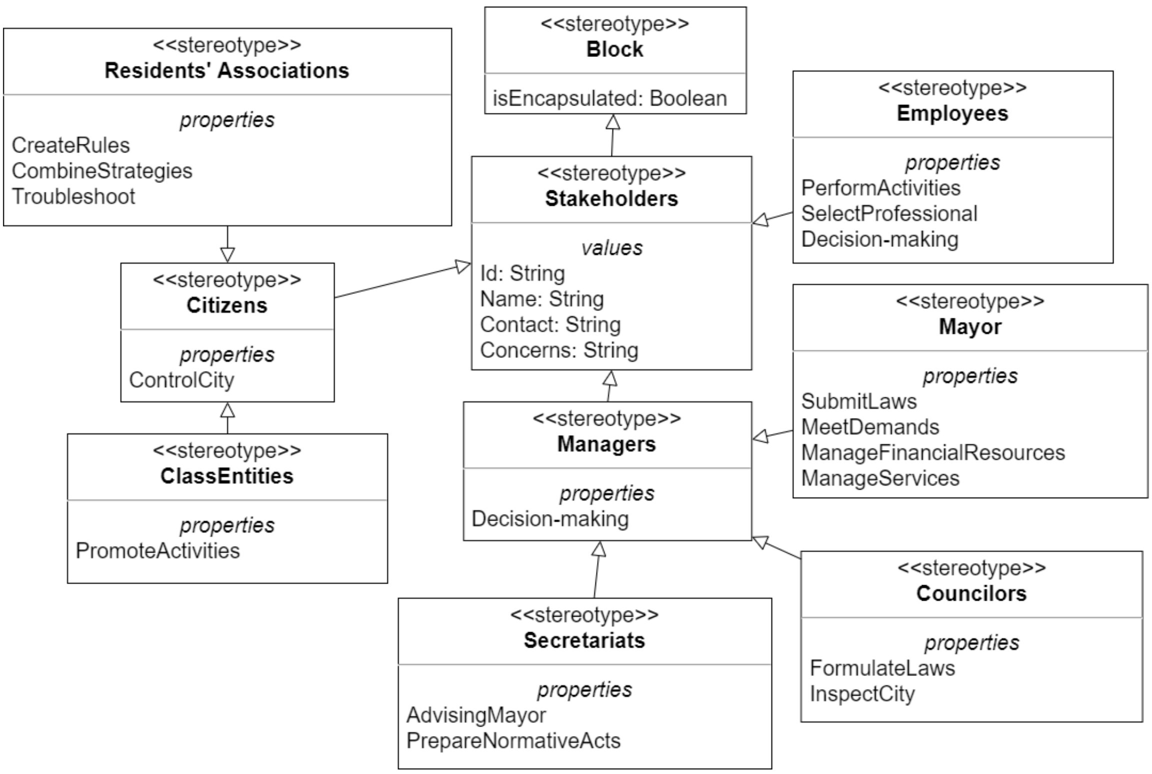
Stakeholders are not limited to individuals or groups that are directly impacted, but also those who have knowledge that can contribute to building a smart city (KINAWY; EL-DIRABY; KONOMI, 2018). Stakeholders use, manage and contribute to the physical aspect and social infrastructure, stakeholders make available their own devices to provide services, participate in coordinated collective activities, bring human capital, activate infrastructure, and generate new values (DUSTDAR; NASTIĆ; ŠĆEKIĆ, 2017).

Castelnovo (CASTELNOVO, 2016) declares that stakeholders make a central role in smart cities, as they are considered direct or indirect beneficiaries of the dimensions of a smart city. It also complements this by stating that there can be no smart city without smart citizens, while citizens can contribute to making cities smarter even without living in cities that implement smart city initiatives, i.e., citizens can contribute to making a city more sustainable and smart even if the city has not taken any initiative that qualifies it as a smart city.

Axelsson and Granath (AXELSSON; GRANATH, 2018) explains that in a smart city there are eight stakeholder groups. The first group is the politicians who initiate and lead the city's development. The second group are the civil servants who make the preparations for decision making. The third group is a municipally-owned company, e.g., a council that plans the development of the city and urban life. The fourth group are the architects who plan and define the development of the physical structures and the content of the city. The fifth group are the construction companies that manage the project. The sixth group are the infrastructure providers, for example, the energy that promotes the development of the city. The seventh group is a partnership with a local university aiming to gather knowledge for the coordination of activities related to the development of the city, the exposure of urban life, and work organization. The eighth group are citizens and businesses that are considered the most important groups in all planning activities of a city.

Galati (GALATI, 2018) declares that stakeholders are varied depending on the size and geographic location of the city, and maybe residents and owners of private to economic businesses in the city, development corporations, and the government. Stakeholders in smart cities generally include local governments, research institutions, grassroots movements, technology trade providers, business owners, tourism boards, and real estate developers.

Figure 11 – Types of Stakeholders.



Source: the author

The person interested in SmartCitySysML can be a citizen, a manager, or an employee, as depicted in Fig. 11. Managers can be the mayor, secretaries, or councilors. Citizens can be class entities or residents' associations.

3.3 Requirements

By definition, a Requirement describes functions and restrictions in detail that should be an objective, a necessity, or a purpose. It is worth pointing out that requirements are difficult to gather and change constantly.

One of the main requirements to transform a city into a smart city is the ability to solve problems from ICTs and IoT because the problems encountered in a smart city can be difficult to solve as they grow and become more complex, also, there are social, economic, racial, regional and gender inequalities (MONZON, 2015).

It is worth mentioning that in smart cities there are other requirements such as contracts and restrictions that can improve services, laws that can not be developed and enforced properly if existing laws are not reviewed from the new demands, for example, user privacy, leadership in smart cities and interoperability, and financial resources that can influence the development of the city through economic growth, innovation and communication (KHATOUN; ZEADALLY, 2017), (CARÈ et al., 2018).

In a smart city, some of the requirements for implementing ICTs and services are described as interoperability, scalability, security, privacy, context awareness, adaptation, extensibility, and configuration to handle Cyber-Physical Systems, IoT, Big Data, and Cloud Computing, as well as data management, heterogeneity, runtime, data access, data processing, service management, and maintenance (SANTANA et al., 2017).

Nuaimi et al. (NUAIMI et al., 2015) declare that in smart cities, the requirements of the applying support to design and implement to search out effective solutions to problems, and these requirements are obtained by understanding the main features and components of the smart city.

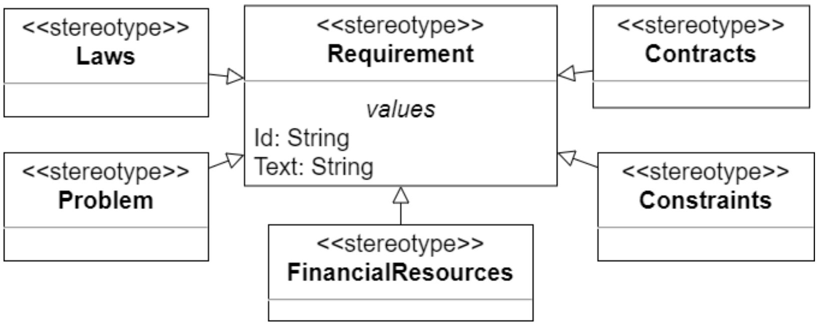
Mehmood et al. (MEHMOOD et al., 2017) assert that the various applications in a smart city require various requirements, for example, low cost, low power consumption, high quality, wider coverage, greater flexibility, high security and privacy, interoperability, and among others.

According to Liu and Huang and Wosinski (LIU; HUANG; WOSINSKI, 2017), smart cities express the daily needs of their citizens, using ICT infrastructures, through the optimization and search for solutions to problems related to sustainability, habitability, and urban development, for example, responsible management of resources and energy efficiency.

Cui (CUI et al., 2018) states that for the construction of a stable and safe smart city, the main requirements are authentication and confidentiality, availability and integrity, detection of intrusion lightweight and prediction, and privacy protection.

The proposed types of requirements proposed in SmartCitySysML are laws, problems, contracts, constraints, and financial resources, as depicted in Fig. 12. These requirements are essential for the development of a sustainable city with good governance.

Figure 12 – Types of Requirements and Needs.



Source: the author

3.4 Solutions

In SmartCitySysML, the solutions, illustrated in Fig. 13, are possible solutions for a city that can be related to transformations for the well-being of the population, so they need elements such as data, assets, devices, sensors, actuators, and machines to be placed at the center of a smart city planning, that is, to be used to designing possible solutions to the identified problems.

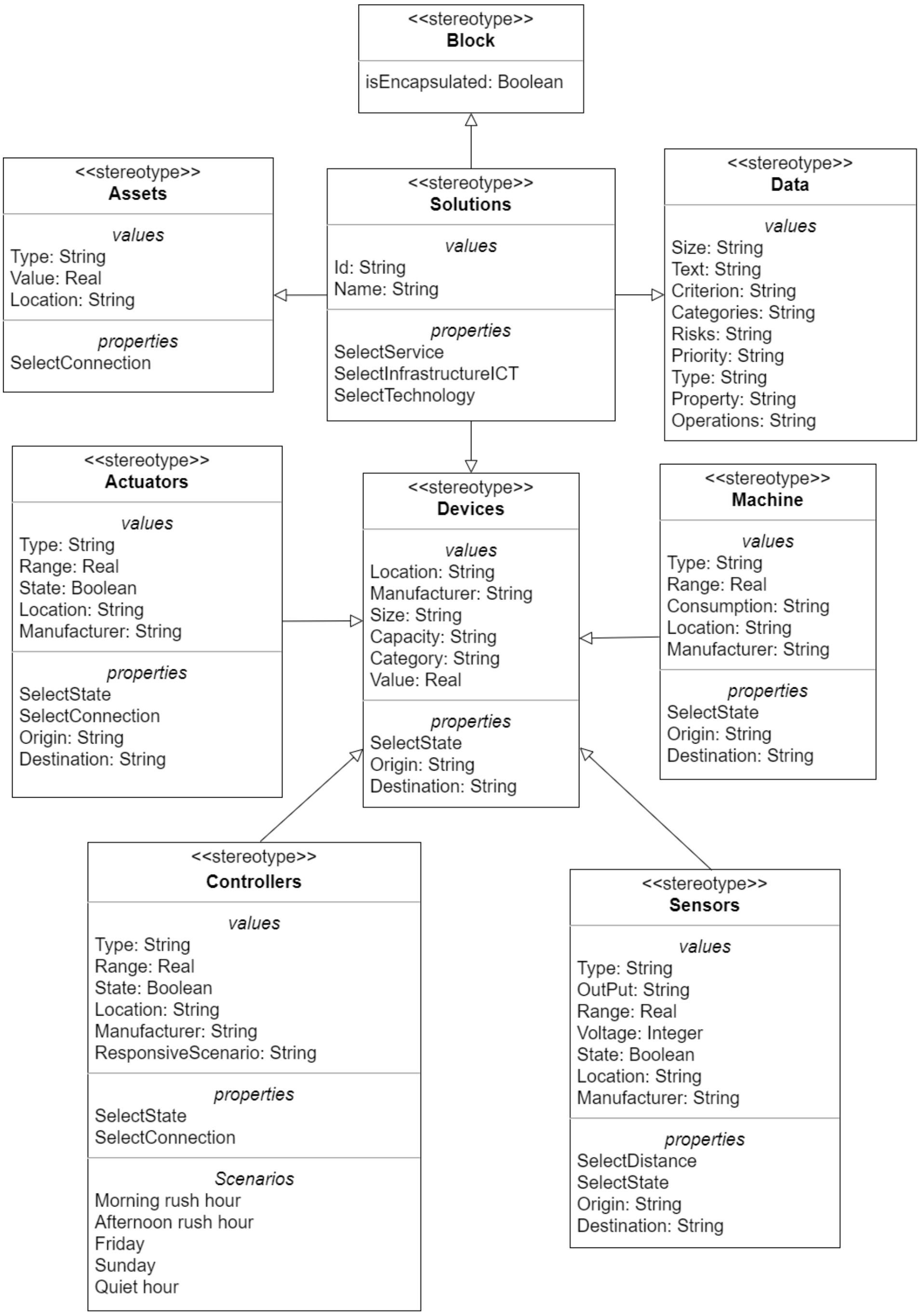
Smart solutions are developed from ICT to increase the effectiveness and efficiency of service delivery and management aimed at sustainability in smart cities, and multiple socioeconomic, environmental, and institutional benefits. In addition, these solutions can influence and transform different urban subsystems providing learning and benefits by stimulating creativity of citizens by offering potential innovative ideas (SHARIFI, 2019).

Sharifi (SHARIFI, 2019) also complements that the application of smart solutions help in the planning and development processes of the city vision in response to the emerging mechanisms of cities, as well as provide opportunities to develop models and/or scenarios that can reduce the effects of future uncertainties by improving forecasting capabilities.

Smart city solutions meet the demands of all possible scenarios, i.e., dimensions (TRILLES et al., 2017). These solutions are considered to be of a high level of technological innovation because they expand the quality of life of its citizens through various management strategies, e.g., resource management and data management, and technological devices, for example, actuators, sensors, controllers, devices, and machines (SINAEEPOURFARD et al., 2019).

Adoption of smart city solutions has proven that ICT can address many challenges such as security, mobility, and sustainability (ELSHENAWY; ABDULHAI; EL-DARIEBY, 2018). Costs

Figure 13 – Elements used in Possible Solutions.



Source: the author

of using ICT to solve challenges is high, so growing cities need funds to finance transformation projects, i.e., provide solutions to the challenges of growing cities both now and in the future (OKAI; FENG; SANT, 2018).

In smart cities, the main problems related to solutions are data access, aggregation, reasoning, access, and service delivery (BELLINI et al., 2018). Thus, smart cities encourage stakeholders, e.g., citizens and authorities, to use and create smart solutions for all dimensions, using innovative, smart, and effective technologies to address contemporary challenges (ZAWIESKA; PIERIEGUD, 2018).

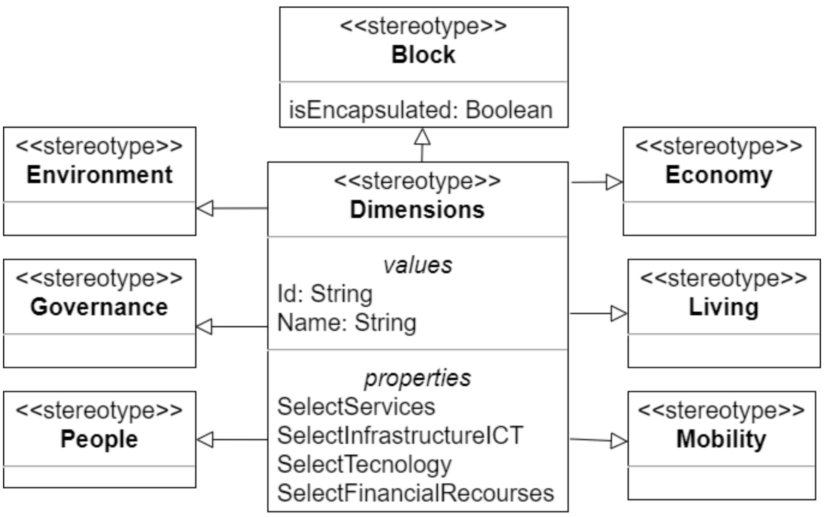
Sarma and Sunny (SARMA; SUNNY, 2017) state that solutions for smart cities are developed based on data and processes. These data and processes serve to plan decision making from the divergent objectives of stakeholders, departments, companies, and groups.

Buuse and Kolk (BUUSE; KOLK, 2019) declare that smart cities solutions deploy ICT-based technologies to address issues related to sustainability, resource efficiency, capacity, and quality optimization of urban services, as well as economic, environmental, and social aspects in areas such as energy, mobility, water, and waste management.

3.5 Dimensions

Dimensions illustrated in Fig. 14 were identified by Giffinger et al. (GIFFINGER et al., 2007). Governance, environment, mobility, economy, people, and living can only be seen as results when the fundamental buildings of smart city are established, e.g., regional competitiveness, social and human capital, ICT, infrastructure, and economy (BOES; BUHALIS; INVERSINI, 2015).

Figure 14 – Dimensions of Interest in a Smart City.



Source: the author

These dimensions of smart cities improve monitoring of the city, as they gather information (incidents or emergencies) from all sources with easy and quick access, act dynamically on the needs of citizens, and comprise useful services and information for better decision making (MUVUNA et al., 2019).

These dimensions are characterized by the intellectual level of human capital needed to support continuous innovation and solve problems or challenges, e.g., social inclusion, quality of life, economic development, human capital development, optimal management of natural resources, and sustainable urban development in general (OJO; DZHUSUPOVA; CURRY, 2016).

These dimensions are technology-based for the use of ICT infrastructures and aim to improve and transform smart city life, based on education, learning, and knowledge, and the cooperation of stakeholders and governments to design and implement smart initiatives (RANDHAWA; KUMAR, 2017).

Therefore, the dimensions of a smart city have relevant factors that reflect the important aspects of each smart characteristic. These dimensions approximate the needs of the applications and the elements in the field of modeling applications in smart cities, both in design and software architecture (NILSSEN, 2018).

Dameri (DAMERI, 2017) declares that the different dimensions of smart cities need to create economic and social values for different stakeholders respecting and understanding the needs and priorities of the city. For this, the main elements of a city must become increasingly intelligent, and the actions planned from these elements must improve everyday life in the city.

Moustaka and Vakali and Anthopoulos (MOUSTAKA; VAKALI; ANTHOPOULOS, 2017) argue that dimensions structure the urban profile helping to reveal important problems of the city and detect unforeseen events that require actions and decisions. However, dimensions can restrict and hinder the development of a comprehensive and appropriate model.

Neves, Neto and Aparicio (NEVES; NETO; APARICIO, 2020) assert that the six dimensions (economy, people, governance, mobility, environment, and life) of smart cities are important for improving urban systems, promoting innovation and development, making cities smarter and more sustainable capable of meeting society's challenges, meeting the needs of businesses, citizens and institutions, and improving quality and performance in all areas, e.g., economy, mobility, energy, security, and sustainability.

4

Design of Smart Cities Dimensions using the SmartCitySysML Profile

The design of dimensions of a smart city focuses on the strategies adopted to identify challenges, for example, cost, efficiency, sustainability, communication, safety, and security. This type of design observes and analyzes both citizens and technological aspects of the city, i.e., ICT, sensors, and IoT that can improve design and planning processes, and thrive on citizens' quality of life (MOHANTY; CHOPPALI; KOUGIANOS, 2016), (MUELLER et al., 2018), (KUMAR et al., 2020).

Dimensions of smart cities are identified and described from factors and characteristics that reflect the important aspects of each smart characteristic, for example, smart people have human and social capital, the smart environment has natural resources, the smart economy has competitiveness, smart mobility has transport and ICT, smart life has a quality of life and smart governance has citizen participation.

Table 1 illustrates the different dimensions described by various authors of a smart city. The authors of the dimensions are on the horizontal, and the dimensions are on the vertical. SmartCitySysML stands for the dimensions described by the author of this thesis, GG stands for Giffinger and Gudrun (GIFFINGER; GUDRUN, 2010), NP stands for Nam and Prado (NAM; PARDO, 2011), R stands for Roche (ROCHE, 2014), J stands for Jucevičius et al. (JUCEVIČIUS; PATAŠIENĖ; PATAŠIUS, 2014), and N stands for Nilssen (NILSSEN, 2018).

In Table 1, it is possible to note that most areas are not yet consolidated in the dimensions of a smart city, for example, in SmartCitySysML, Giffinger and Gudrun (GIFFINGER; GUDRUN, 2010), and Nam and Prado (NAM; PARDO, 2011) the people dimension is presented. In SmartCitySysML, Giffinger and Gudrun (GIFFINGER; GUDRUN, 2010), and Nilssen (NILSSEN, 2018) the governance dimension is presented, in the works of authors Nam and Prado (NAM; PARDO, 2011), Roche (ROCHE, 2014), Jucevičius et al. (JUCEVIČIUS; PATAŠIENĖ; PATAŠIUS, 2014) and Nilssen (NILSSEN, 2018) the technology dimension is presented, and the other dimensions are presented only once.

Table 1 – Dimensions for Smart City.

	SmartCitySysML	**GG**	**NP**	**R**	**N**	**J**
People	•	•	•			
Governance	•	•			•	
Economy	•	•				
Mobility	•	•				
Environment	•	•				
Living	•	•				
Technology			•	•	•	•
Institutions			•			
Intelligent				•		
Open				•		
Live				•		
Collaborative					•	
Experimental					•	
Agile						•
Learning						•
Knowledge-driven						•
Network						•
Innovation						•

Source: the author

It is worth noting that although the dimensions proposed by Giffinger and Gudrun (GIFFINGER; GUDRUN, 2010) and the dimensions proposed in the SmartCitySysML profile are the same, they have different characteristics. The characteristics and factors of each dimension of the SmartCitySysML profile are described in the following sections, while the characteristics and factors proposed by Giffinger and Gudrun (GIFFINGER; GUDRUN, 2010) are:

- Economy dimension: an innovative spirit, entrepreneurship, economic image and trademarks, productivity, the flexibility of labor market, international embeddedness, and ability to transform;

- People dimension: level of qualification, affinity to lifelong learning, social and ethnic plurality, flexibility, creativity, cosmopolitanism/open-mindedness, and participation in public life;

- Governance dimension: participation in decision making, public and social services, transparent governance and political strategies and perspectives;

- Mobility dimension: local accessibility, national and international accessibility, availability of ICT-infrastructure and sustainable, innovative, and safe transport systems;

- Environment dimension: lack of pollution of natural conditions, pollution, environmental protection, and sustainable resource management;

- Living dimension: cultural facilities, health conditions, individual safety, housing quality, education facilities, touristic and social cohesion.

The proposed dimensions in the SmartCitySysML profile were identified and described from essential factors and characteristics for a smart city aiming to improve efficiency, sustainability, and quality of life for citizens living in these cities. For the design of the SmarCitySysML dimensions, the SysML Internal Block diagram (IBD) is used to describe the main dimensions of a smart city.

4.1 People

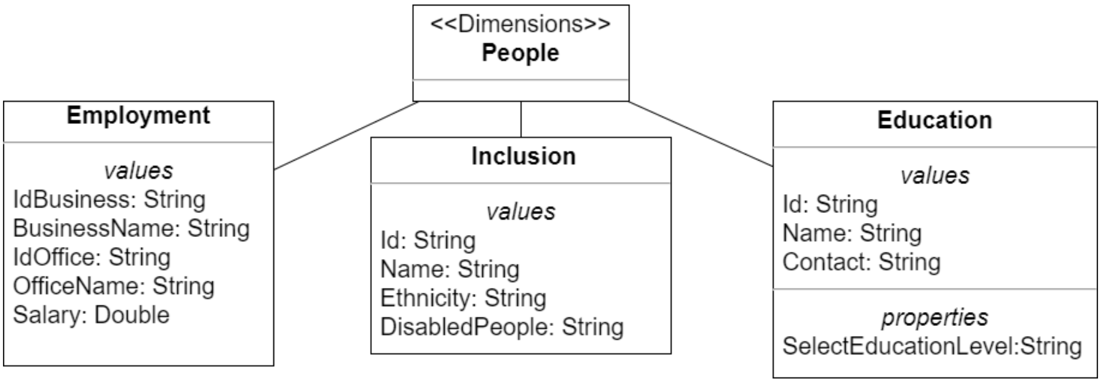
Smart people concerns not only individuals but also communities and groups such as government, business, institutions, and social organizations. People are the main actors in the development of the smart city. On the other hand, the development of the smart city will take into account the needs of people (SHEN et al., 2018). Smart people are concerned with improving creativity and promoting innovation from lifelong learning, using technology to enable work and ICT to facilitate human resources, capacity management, and access to education and training (CAMERO; ALBA, 2019).

In the people dimension, people's needs have to be identified, modeled, understood, and designed as solutions to provide inclusive education and training that promote creativity and innovation (CALDERÓN; LÓPEZ; MARÍN, 2017). Kumar and Dahiya (KUMAR; DAHIYA, 2017) compliment by stating that smart people are fundamental in a smart city. Smart people are open-minded, have a multicultural perspective, maintain a healthy lifestyle, and are actively involved in the sustainable, efficient, and harmonious development of their cities. Therefore, without the active participation and involvement of smart people, a smart city will be inneffective.

Smart cities demonstrate that people are important to the solution scenario because the devices used by people become sensors and smart objects capable of monitoring human behavior in the city and contributing to the definition of smart policies, for example, efficient consumption of water and energy, mobility, traffic, and environmental monitoring (DELMASTRO; ARNABOLDI; CONTI, 2016).

People, as depicted in Fig. 15, refers to social and human capital, social learning and education, the level of qualification of women and men from different backgrounds, motivation to learn and participate in the co-creation of public life, affinity to lifelong learning, social ethnic plurality, open-mindedness and individuals' participation in public life. Some values are equity, creativity, flexibility, cosmopolitanism and tolerance (GIFFINGER; GUDRUN, 2010), (COHEN, 2012), (STAFFANS; HORELLI, 2014), (MOUSTAKA et al., 2018).

Figure 15 – People Dimension of a Smart City.



Source: the author

4.2 Economy

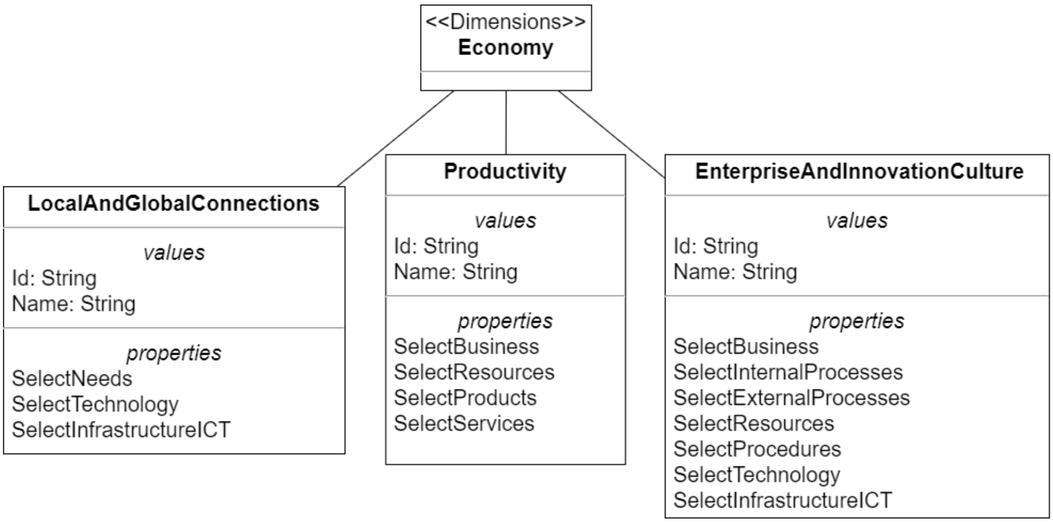
Economy is the stimulus to promote the development of a city and the main driver to implement a smart city initiatives related to production, distribution, and services. A smart economy measures the performance of innovation, competitiveness, capacity to transform and drive the urban economy. These measures reflect economic competitiveness, entrepreneurship, brands, productivity, labor market flexibility, and the integration of national and global markets (SHEN et al., 2018), (NEVES; NETO; APARICIO, 2020).

Smart economy uses technology and innovation to exploit resources, develop and implement solutions, overcome challenges, create a favorable economic environment, strengthen developing businesses, promote employment, stimulate competitiveness and urban growth from knowledge-based industries and technology-focused services with a focus on the quality of life (MATTONI; GUGLIERMETTI; BISEGNA, 2015), (ANTHOPOULOS, 2017), (PRAHARAJ; HAN; HAWKEN, 2018).

The smart economy dimension requires a smart city to have attributes such as entrepreneurial leadership, economic DNA, valuing creativity, preparing for the challenges and opportunities of economic globalization, as well as driving innovation, making strategic investments, standing out in productivity and flexibility, and insisting on balanced and sustainable economic development and growth (KUMAR; DAHIYA, 2017).

Economy, as depicted in Fig. 16, refers to innovative spirit, entrepreneurship, economic image and trademarks, productivity, the flexibility of labor market, international embeddedness, economic transformations, local and global interconnectedness, effective production of goods and services for new business models, enhanced by connectivity through ICT (GIFFINGER; GUDRUN, 2010), (COHEN, 2012), (STAFFANS; HORELLI, 2014), (MOUSTAKA et al., 2018).

Figure 16 – Economy Dimension of a Smart City.



Source: the author

4.3 Environment

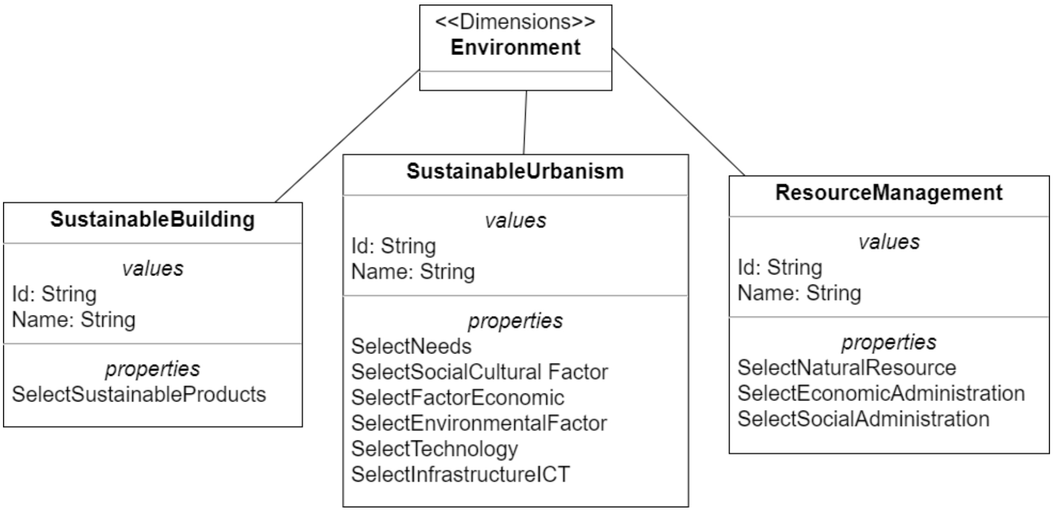
The smart environment transforms the processes and resources of sustainable urban development, through the use of infrastructure and technology, generating significant impacts on city management, i.e., consumption of natural resources and energy, air emissions, and waste disposal, to change people's habits and avoid waste, e.g., improving and benefiting the environment. However, the increasing transformation of urban environments can cause sustainability challenges, for example, climate change (ALETÀ; ALONSO; RUIZ, 2017), (CUI et al., 2018).

The sustainability of the smart environment, for example, air quality, ecological awareness, and sustainable management of resources are achieved when environmental infrastructure, e.g., waterways, sewers, and green spaces are built based on the use of natural resources and green energy to seek preservation and better quality of life (ARROUB et al., 2016), (DAMERI, 2017).

The smart environment dimension uses technological resources to detect, act, communicate and enable the infrastructure and technologies to provide services, acquire and exploit knowledge about the environment, so that its citizens live and protect nature, as well as can adapt their preferences and needs in the present and future (JOSHI et al., 2016), (CICIRELLI et al., 2017), (SILVA; KHAN; HAN, 2018), (KUMAR, 2020a).

Environment, as depicted in Fig. 17, refers to the care with natural resources and planetary culture, that is, it includes sustainable resource management, pollution reduction, and environmental protection with green construction, green urban planning, green production, green buildings, and consumption of green energy (GIFFINGER; GUDRUN, 2010), (COHEN, 2012), (STAFFANS; HORELLI, 2014), (MOUSTAKA et al., 2018).

Figure 17 – Environment Dimension of a Smart City.



Source: the author

4.4 Mobility

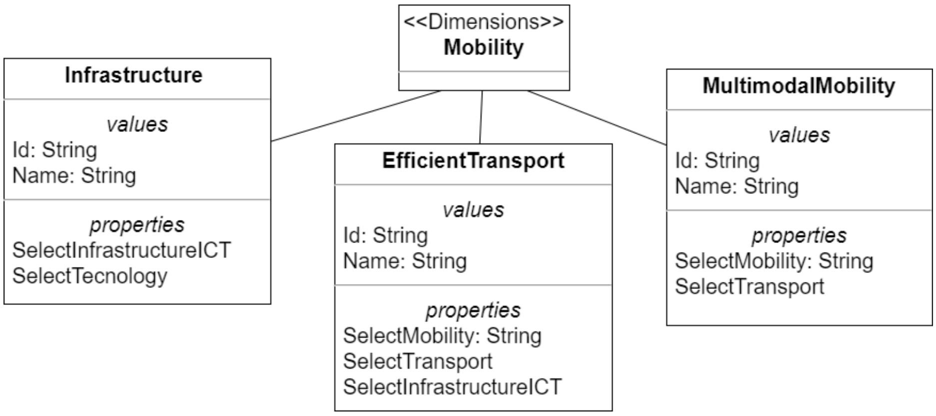
Mobility facilitates the displacement of people and goods in a city and also causes the development of economic and social activities. Currently, mobility is related to the use of technologies and infrastructures as a form of possible solutions to different problems that exist in almost every city (FARIA et al., 2017), (JEEKEL, 2017).

In smart cities, mobility is organized into accessibility, sustainability, data, ICT, and services and refers to both movements within the city, and delivery of goods, as well as communication technologies and infrastructures throughout the city to collect feedback from citizens on the quality of life in cities and public transport services, real-time monitoring and flexible reactions to problems (CUI et al., 2018), (BATTARRA et al., 2018).

The mobility dimension aims to facilitate people of flexibility within a city and consequently generates benefits such as reduced traffic, reduced travel time and costs, reduced pollution, reduced noise pollution, and higher safety during travel. Furthermore, mobility can change constantly, have immediate communication with mobile applications and ensure an intelligent, easy, and smooth travel process (ŠURDONJA; GIUFFRÈ; DELUKA-TIBLJAŠ, 2020).

Mobility, as illustrated in Fig. 18, refers to sustainable innovative, safe transport systems, mixed modal access, logistics, and communication systems, availability of ICT infrastructure, local and international accessibility. Real-time information improves the management of public and personal mobility, increasing the use of appropriate mobility options and chains, for example, trams, trains, subways, cars, and bicycles (GIFFINGER; GUDRUN, 2010), (COHEN, 2012), (STAFFANS; HORELLI, 2014), (MOUSTAKA et al., 2018).

Figure 18 – Mobility Dimension of a Smart City.



Source: the author

4.5 Living

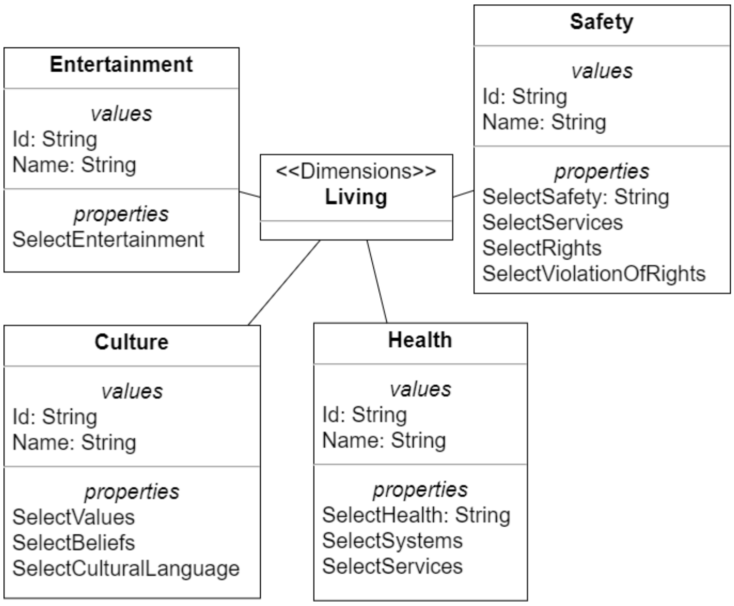
Living in a smart city provides quality of life, social inclusion, quality in urban services, sustainability, management of natural resources sustainably and safely for its citizens from the use of ICT within an interactive and innovative infrastructure (KIRIMTAT et al., 2020), (KUMAR, 2020b), (QUIJANO-SÁNCHEZ et al., 2020).

Smart living covers areas of the city such as public safety, health, education, tourism, and intelligent buildings. These areas increase quality of life of the citizens of a smart city. However, smart living needs to be composed of infrastructure, systems, sensors, and intelligent devices to focus on climate, education, tourism, health, safety, the environment, public transport, and people flows (ISMAGILOVA et al., 2019), (KIRIMTAT et al., 2020).

The living dimension is considered a key element for the development and management of a smart city. Services provided by this dimension are based on ICT for the dissemination of information and the involvement of citizens in cultural activities and tourism (YEH, 2017), (GIRARDI; TEMPORELLI, 2017), (VÁZQUEZ et al., 2018), (MACKE et al., 2018).

Living, as depicted in Fig. 19, refers to the quality of life and safe environments. It comprises an infrastructure to support everyday life, that is, decent housing options, good health conditions, work opportunities or significant activities, access to nature, touristic attractiveness, individual safety, housing quality, educational and cultural facilities incorporated into social cohesion, enhanced by co-governance(GIFFINGER; GUDRUN, 2010), (COHEN, 2012), (STAFFANS; HORELLI, 2014), (MOUSTAKA et al., 2018).

Figure 19 – Living Dimension of a Smart City.



Source: the author

4.6 Governance

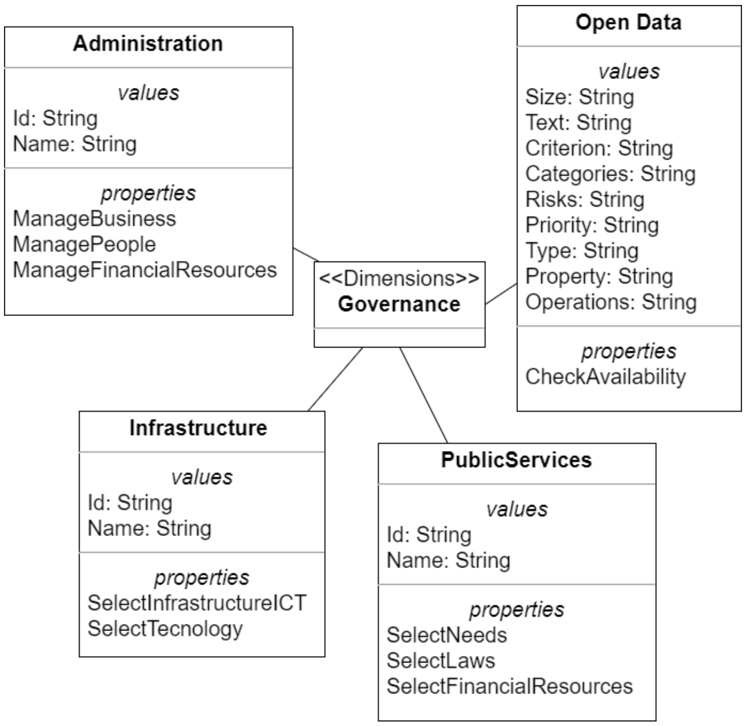
Smart governance is composed of components, measurements, contextual factors, and outcomes. Components are stakeholders, structures and organizations, processes, roles and responsibilities, technology and data, legislation and policies, and exchange arrangements. Measurements are based on components. Contextual factors are the degree of autonomy and local conditions. Outcomes are substantive outputs and procedural changes (RUHLANDT, 2018).

Smart governance focuses primarily on how governments can use ICT innovations to develop better policies and expand the delivery of desirable services to citizens through smart infrastructure. In this way, municipal governments can rethink, change and improve their government routines, procedures and processes with the help of stakeholder participation and collaboration (EDELENBOS et al., 2018), (LIN, 2018), (FARAJI; NOZAR; ARASH, 2019).

The smart governance dimension plays an important role in a smart city. The goal of smart governance is to better serve citizens and communities by linking data, institutions, procedures, and physical infrastructure based on ICT. Also, a smart government allows citizens to be involved in city planning and public decisions. Therefore, the smart government can improve efficiency at the same time as increasing the transparency of information (CUI et al., 2018).

Governance, as depicted in Fig. 20, refers to public strategies and policies, including urban planning, which enables the co-production of public services, that is, participation in decision making, public and social services, transparent governance, and political strategies and perspectives. Governance needs to be a transparent process and open data that allows a variety of participation at different levels for decision making. It is characterized by the orchestration and balance of processes, partnerships, networks, and formal, semi-formal and informal spheres (GIFFINGER; GUDRUN, 2010), (COHEN, 2012), (STAFFANS; HORELLI, 2014), (MOUSTAKA et al., 2018).

Figure 20 – Governance Dimension of a Smart City.



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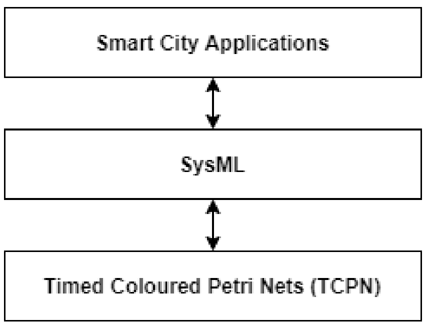
5

Design of Smart Cities Application with SmartCitySysML: A Case on Urban Traffic Signal Control

A SysML model represents designed systems by analyzing behavioral and structural aspects that can be used to evaluate alternative options, risks, and conflicts in advance, as well as verify traceability and feasibility relationships before the system is implemented, but has limitations for simulation and validation of model specifications. A Petri Net model describes explains the physical behavior of a system, allows analysis of the model to identify conflicts, cycles, unexpected behavior, and deadlocks, and verifies and validates model specifications through analysis of properties. For this reason, the use of a SysML model allows verification of the specification using the execution capabilities of dynamic models, which makes the specification amenable to analysis by simulation, and the use of a Petri Net model allows the mathematical representation as well as analysis of information about the behavior of an existing model (JAMRO; RZONCA; RZĄSA, 2015).

Figure 21 – Layers to Design an Urban Traffic Signal Control System.



Source: the author

This chapter details an application of SmartCitySysML to model an urban traffic signal control system and then verify some of its properties. To better understand this chapter, Figure 21 illustrates the SysML, Smart City, and Timed Coloured Petri Nets (TCPN) layers used to design an urban traffic signal control system. This chapter is divided into the specification of characteristics related to urban traffic signal control, the description of SysML extensions, and Petri Net and TCPN to model the problem.

The choice of using Petri Net is because it is possible to separately model each of the elements of an urban traffic signal control system (sensor, controller, and actuator), as Petri Net sub-models to describe the behavior of these elements. Then illustrate with TCPN the behavior of the combination of the sub-models designed with Petri Net, analyze the behavioral properties of the TCPN model through simulation and property verification, and describe timing constraints. For this case study, the software requirements for the intersection controller are inspired by examples presented elsewhere (LAPLANTE, 1992), (SILVESTRE; SOARES, 2012).

5.1 Case Study: Urban Traffic Signal Control

The main objective of this section is to detail the architectural elements of an application for design an urban traffic signal control system. Traffic signal control is considered a competitive traffic management strategy to improve mobility and address environmental issues in urban areas, as they regulate traffic flows to achieve a more efficient traffic management strategy, i.e., one of the main tools to control congestion on roads (LE et al., 2015), therefore, they are an important and challenging problem in the real world, which aims to monitor and improve traffic congestion (YAU et al., 2017), (AN et al., 2017), (WEI et al., 2019).

Traffic signals are the most basic instrument for road traffic data collection of a city, that is, they allow the management of traffic flow of vehicles and pedestrians, as well as the starting point for data acquisition. For example, vehicle and pedestrian counting, traffic speed, and congestion. Traffic signal control is an important and challenging problem in the real world, as traffic signals can provide potential solutions to ensure improved and efficient transport and consumption, energy consumption, environmental protection, increased productivity, and citizen satisfaction (AN et al., 2017), (WEI et al., 2019), (GUO; LI; BAN, 2019).

Traffic signals at intersections are control devices applied to urban traffic and aim to optimize the flow of vehicles, enabling safe, efficient, and adequate crossings. When these signals are installed and operated properly, they provide safe crossing for vehicles, reducing the frequency and severity of accidents and interruptions in heavy flows. However, when installed and operated incorrectly, they can cause delays, increase the number of accidents, and increase red signal trespassing (SILVESTRE; SOARES, 2012).

Current traffic signal control systems in use still rely heavily on simplified methods used in the control rules to decide whether to maintain or change the current phase (WEI et al., 2019).

An intersection between two or more roads is a complex infrastructure, thus the movements cannot be performed simultaneously, as they conflict with each other. As the traffic flow at the intersection changes constantly, depending on weather conditions, day of the week, and period of the day, in addition to road works and accidents that further influence complexity and performance, it is necessary to make decisions, that is, establish rules for control the right path for vehicles and pedestrians (ASAITHAMBI; KUTTAN; CHANDRA, 2016).

5.1.1 User requirements

Functional user requirements are presented as follows, at a high degree of abstraction, i.e., user requirements, to describe the problem of modeling an urban traffic signal control system presenting high vehicle flow. Main users are Citizens of stereotype Stakeholders from SmartCitySysML. These requirements were presented before in (SOUZA; MISRA; SOARES, 2020), except for requirements FR04, FR17, FR18, FR19, FR20, FR21, FR22 which are new.

- **FR01:** The system shall control the vehicle traffic pattern at the intersection.
- **FR02:** The system shall control the pedestrian traffic pattern at the intersection.
- **FR03:** The system shall store the vehicle flow on the roads.
- **FR04:** The system shall store the flow of pedestrians on the roads.
- **FR05:** The system shall control the traffic pattern related to each road.
- **FR06:** The system shall allow a fixed traffic management policy.
- **FR07:** The system shall allow a managed traffic management policy.
- **FR08:** The system shall allow an adaptive traffic management policy.
- **FR09:** The system shall allow the synchronization of traffic signals.
- **FR10:** The system shall allow choosing a priority route.
- **FR11:** The system shall allow detection of the presence of pedestrians.
- **FR12:** The system shall allow personal maintenance.
- **FR13:** The system shall allow remote maintenance.
- **FR14:** The system shall maintain the vehicle traffic history on the roads.
- **FR15:** The system shall maintain the history of traffic policies in the periods of the year.
- **FR16:** The system shall be able to implement new traffic policies.

- **FR17:** The system shall provide convenient means to manage the task and scenario allocation processes.
- **FR18:** The system shall provide convenient means to distribute the tasks and scenarios according to the dynamic context of traffic management.
- **FR19:** The system shall provide convenient means for defining various kinds of concurrent task and scenario execution and synchronization.
- **FR20:** The system shall provide flexible means to authorize tasks and scenarios.
- **FR21:** The system shall be able to express different dynamic tasks and scenario prioritization schemes.
- **FR22:** The system shall be able to support unanticipated tasks and scenarios.
- **FR23:** The system shall store incidents at the intersection.
- **FR24:** The system shall allow automatic operation of traffic signals.
- **FR25:** The system shall store the incidents that occurred in software and hardware.

5.1.2 Modeling Urban Traffic Signal Control with SmartCitySysML

For modeling an urban traffic signal control system, Fig. 22 shows a region that presents high traffic flow in a city in northeastern Brazil. This region is composed of six traffic signals, illustrated by the black circles. In this thesis, the two chosen intersections are controlled by traffic signals, limiting left turns on each road.

Fig. 23 illustrates the traffic signals chosen from this region to model this case study. Intersections in this region can be improved by providing green waves for the main roads (A and B), that is, providing maximum time to the green phase in a sequence of junctions, so that vehicles can cross as much as possible with few stops. It is worth noting that this region presents high flow of vehicles and has one traffic signal for each road. The SmartCitySysML Requirements model is intended to provide a bridge between traditional requirements and other models.

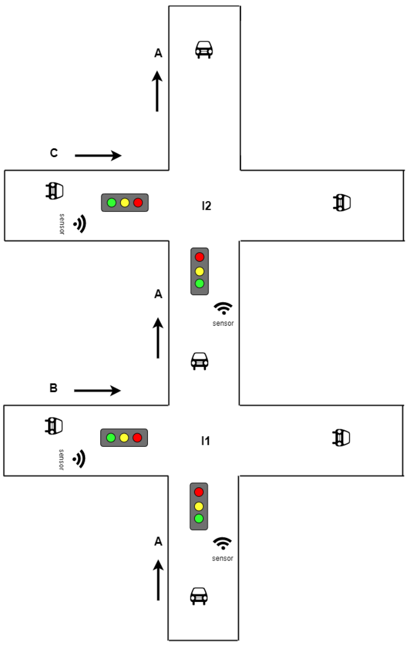
Fig. 24 illustrates a SmartCitySysML Sequence diagram (SD) with an interested party that initiates the behavior by sending a message to a sensor. The sensor sends a message to the traffic controller. After evaluating current traffic, the controller assigns a response scenario (morning rush hour, afternoon rush hour, accidents, or quiet time), that is, it sends the command (green, red, or yellow signal) to the actuator (traffic signal).

Fig. 25 illustrates a SmartCitySysML Block Definition diagram (BDD) which includes the elements needed to solve the problem listed in this section. At this point, it is important to mention that in the proposed approach, concurrent behavior is modeled by synchronizing multiple Block Definition diagrams (BDD) via events.

Figure 22 – Region of the Urban Network with Visualization of Traffic Signals.

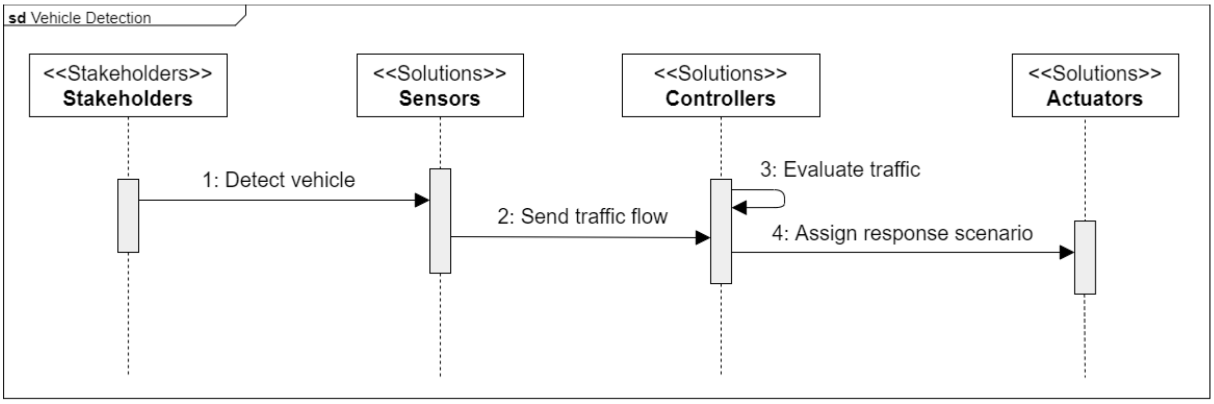
Source: the author

Figure 23 – Specific Region of the Urban Network with Visualization of Traffic Signals.



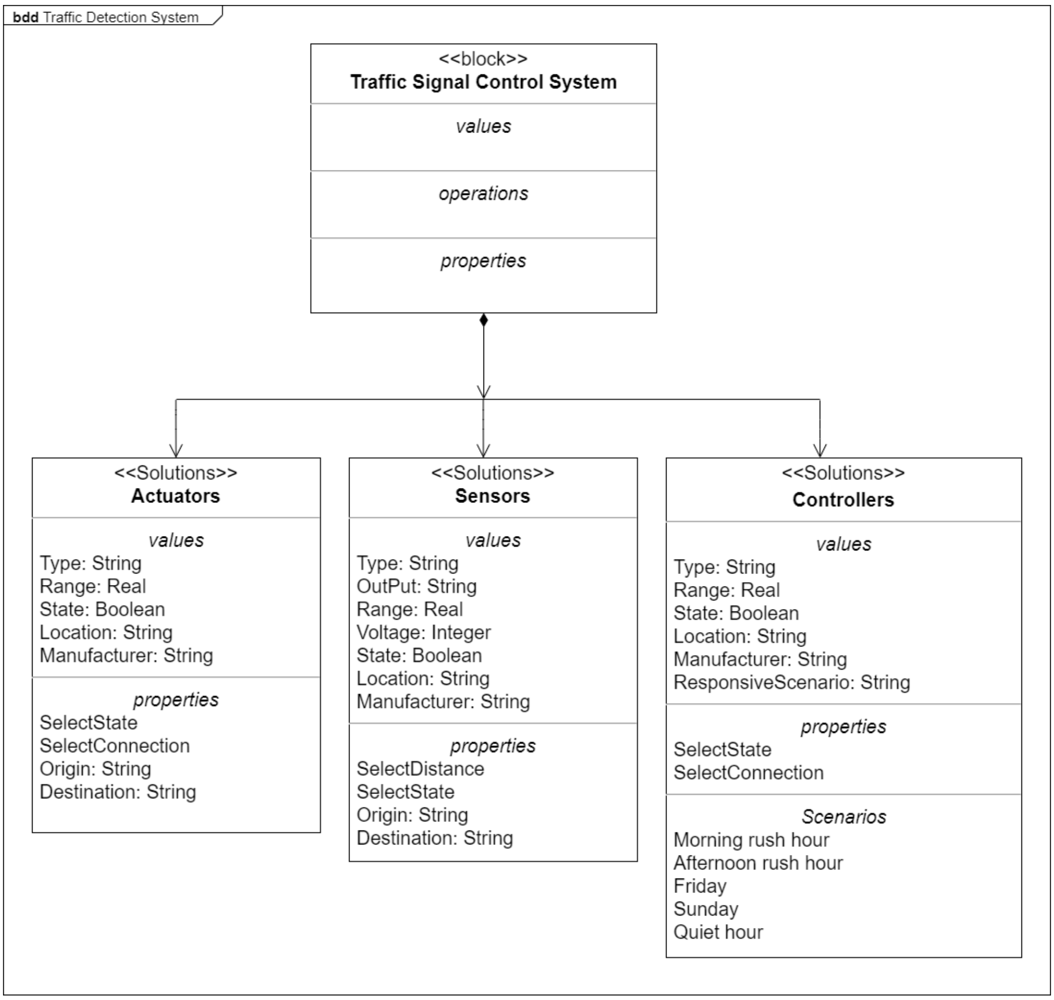
Source: the author

Figure 24 – SmartCitySysML Sequence diagram for Representing Vehicle Detection.



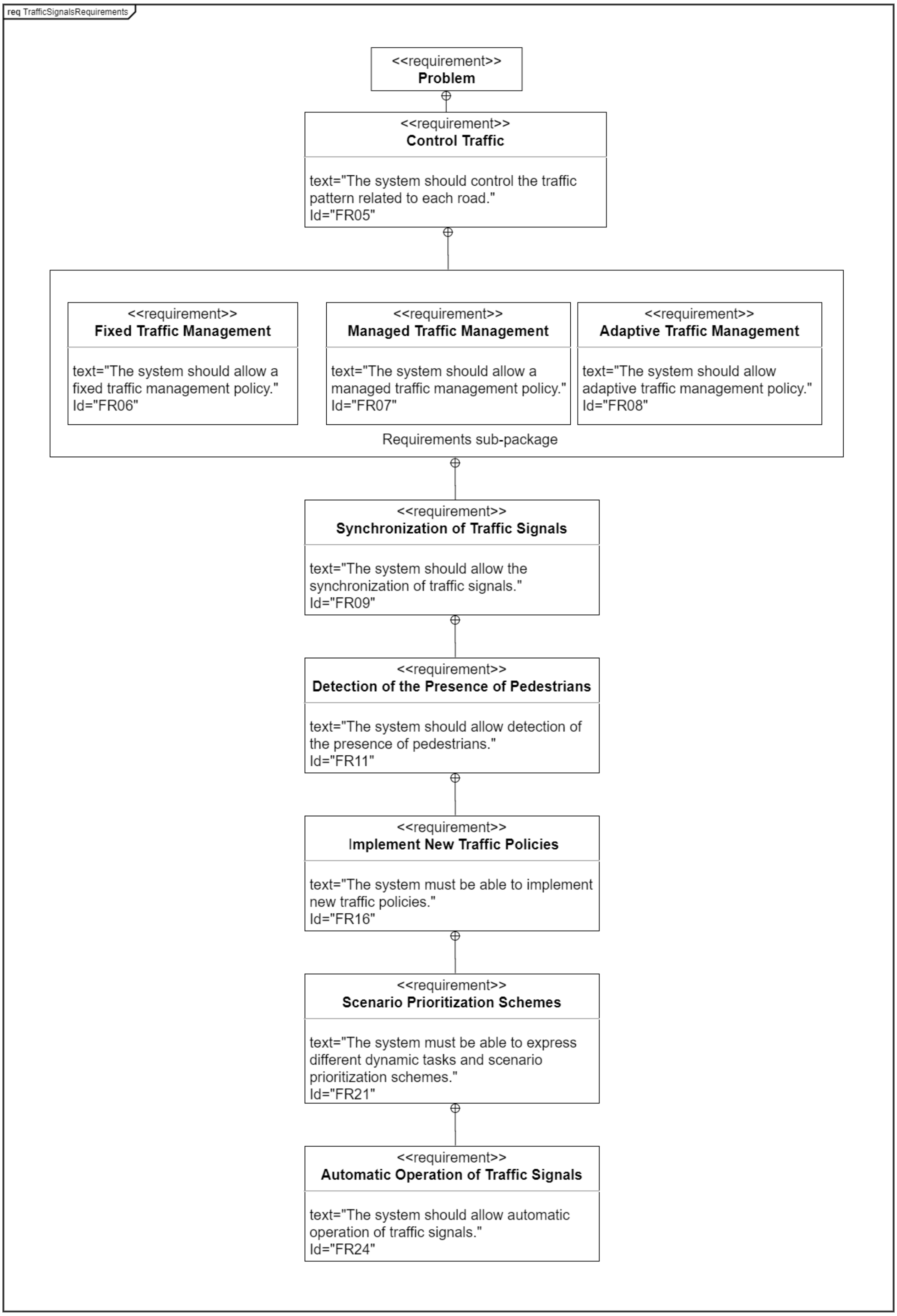
Source: the author

Figure 25 – SmartCitySysML Block Definition diagram for Traffic Signal Control System.



Source: the author

Figure 26 – SmartCitySysML Requirements diagram for Traffic Signals Requirements.



Source: the author

Fig. 26 depicts the SmartCitySysML Requirements diagram (REQ), considering the user requirements described previously and the SmartCitySysML profile using the Problem stereotype. Given this stereotype, the system must control traffic on roads, manage traffic, synchronize traffic signals, detect the presence of pedestrians, implement new traffic policies, scenario prioritization schemes, and automatic operation of traffic signals. In Fig. 26, the following requirements, FR05, FR06, FR07, FR08, FR09, FR11, FR16, FR21, FR24 are selected among the twenty-five user requirements described above for illustration.

5.2 Formal Design and Verification of Urban Traffic Signal Control System

This section describes formal modeling and model verification of properties developed for the urban traffic control system through a model with the Petri Net and the same model illustrated with the TCPN. The Petri Net model is composed of the basic architectural elements (sensor, controller, and actuator) designed as sub-models to describe the behavior of each element. The TCPN model illustrates the behavior of the combination of these elements, analyzes the behavioral properties of this model through simulation and property verification, and describes the timing constraints. Therefore, the focus is to model the behavior of urban traffic signals after their modeling using the SmartCitySysML profile through the SysML Requirements (REQ), Block Definition (BDD), and Sequence (SD) diagrams.

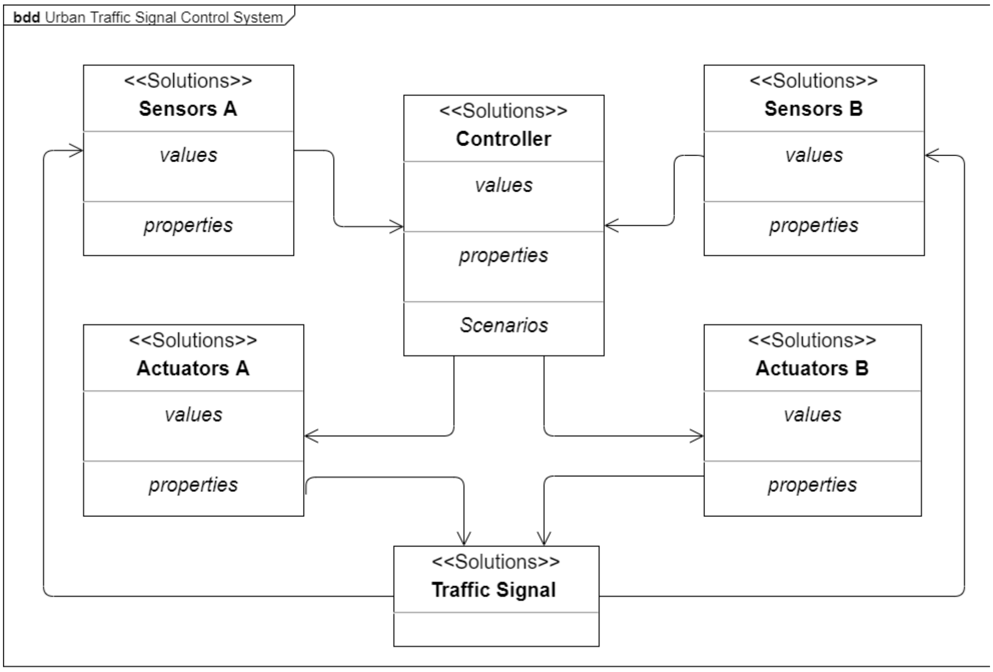
5.2.1 Modeling Basic Architectural Elements of an Urban Traffic Signal Control with Petri Net

Fig. 27 illustrates a SmartCitySysML Block Definition diagram (BDD) that includes elements of the architecture of an urban traffic signal control. The controller, sensor, and actuator elements are specified using components of Petri Net. The sensor sends information about the state of the traffic to the controller. The controller sends signals to the actuator (traffic signals), and the actuator regulates traffic.

Modeling of the controller, sensor, and actuator elements of an urban traffic control is modeled as a Petri Net with modular composition method, i.e., modular Petri Net are illustrated in Fig. 30, 29, 28, respectively.

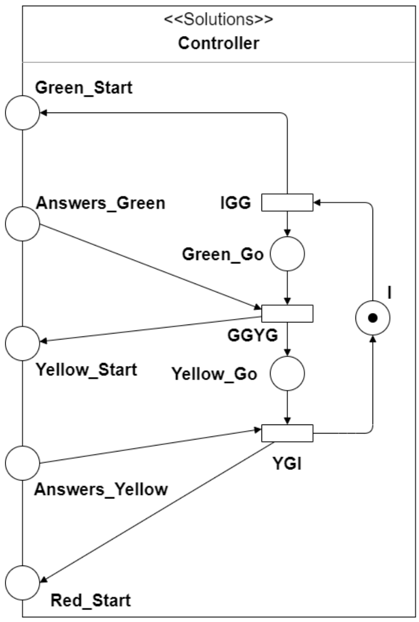
Fig. 28 shows the controller model for controlling the traffic signal of an intersection. This model is composed of places *I, Green_Go, Yellow_Go, Green_Start, Answers_Green, Yellow_Start, Answers_Yellow, and Red_Start* and transitions *IGG, GGYG, and YGI*. For example, the controller *I* sends the green signal (token) command to the *Green_Go* actuator when the transition *IGG* is enabled and deposits a token in place *Green_Start*.

Figure 27 – SmartCitySysML Block Definition diagram for the Architecture of an Urban Traffic Signal Control System.



Source: the author

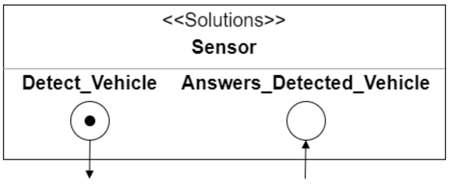
Figure 28 – SmartCitySysML Block Definition diagram for the Controller Components.



Source: the author

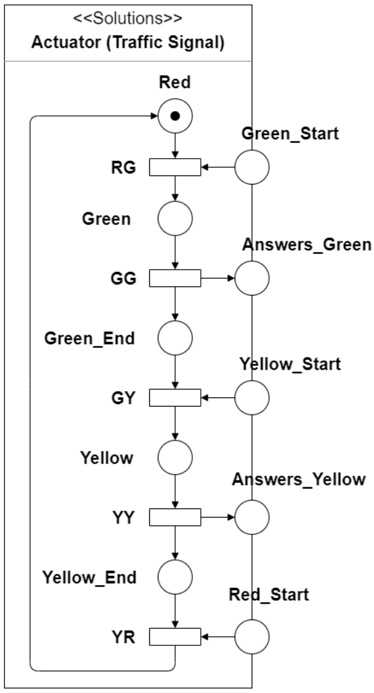
Fig. 29 shows the sensor model. This model is composed of places *Detect_Vehicle and Answers_Detected_Vehicle*, place *Detect_Vehicle* sends information (token) to the controller warning that a vehicle has been detected and place *Answers_Detected_Vehicle* sends information (token) from the controller to the sensor as a form of response.

Figure 29 – SmartCitySysML Block Definition diagram for the Sensor Components.



Source: the author

Figure 30 – SmartCitySysML Block Definition diagram for the Actuator Components.

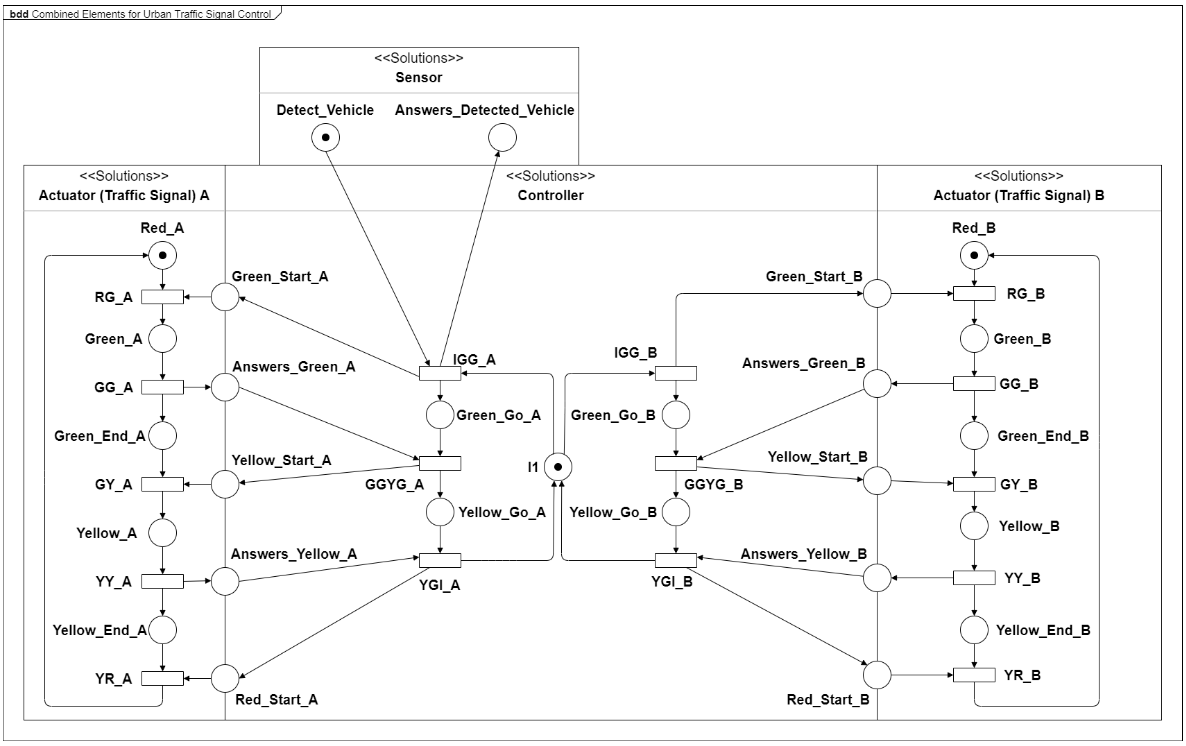


Source: the author

Fig. 30 shows the model of the actuator (traffic signal). This model consists of three phases (green, yellow, and red) together with the requests from the signal to the controller and the responses from the controller to the signal, i.e., places *Red, Green, Green_End, Yellow, and Yellow_End* represent the signal and places *Green_Start, Answers_Green, Yellow_Start, Answers_Yellow, and Red_Start* represent the solicitations and responses between actuator and controller. For example, place *Green_Start* receives from the controller the response of the request to start the green phase of the corresponding road section, and place *Red_Start* receives from the controller the response of the request to start the red phase of the corresponding road section.

Fig. 31 shows, at an abstract modeling level, the combination of SmartCitySysML Block Definition diagram (BDD) for the urban traffic control elements (actuator in Fig. 30, sensor in Fig. 29 and controller in Fig. 28) for the region chosen in this case study, i.e., I1 composed of two traffic signals (A and B), a sensor and a controller for these signals. At this intersection, the A junction of the road has priority over the B one, thus the sensor is in the A junction of the road. A similar design is used for the sensor, controller, and actuator related to the other intersections of the region illustrated in Fig. 22. It is worth noting that this Fig. 31 is depicted from the SmartCitySysML Block Definition diagram (BDD) in Fig. 27 and describes that it is possible to design the internal behavior of a SmartCitySysML Block Definition diagram (BDD) as a Petri Net model.

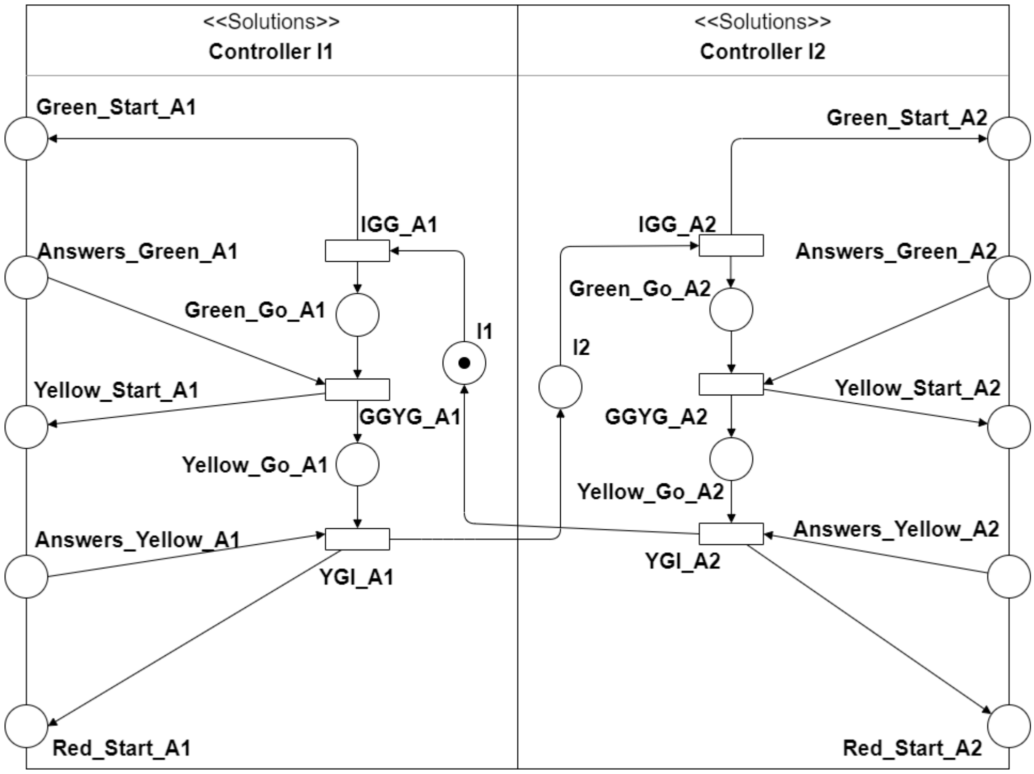
Figure 31 – SmartCitySysML Block Definition diagram of Combined Petri Net Elements for Urban Traffic Signal Control.



Source: the author

Fig. 32 shows the behavior of the SmartCitySysML Block Definition diagram (BDD) of the controllers for intersections I1 and I2 of a bustling region, i.e., when the controller for intersection I1 sends the green signal to intersection I1, the controller for intersection I1 also sends the green signal to the controller for intersection I2. A similar design is used for the other controllers for the other intersections in the region shown in Fig. 22.

Figure 32 – Petri Net for an Urban Traffic Signal Control (I1 and I2).



Source: the author

5.2.2 Modeling Urban Traffic Signals with Timed Coloured Petri Nets

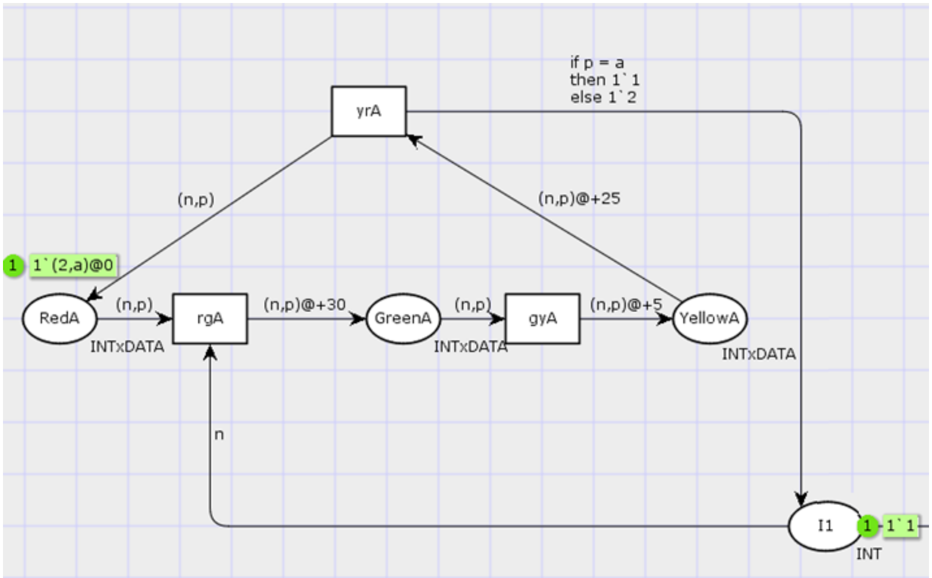
Intersections presented in Fig. 23 can be improved by providing green waves for the main roads, that is, giving maximum time to the green phase in a sequence of junctions, so that vehicles can cross as much as possible with few stops.

Using the SmartCitySysML profile, the region illustrated in Fig. 23 and the SmartCitySysML Block Definition diagram illustrated in Fig. 25, an urban traffic signal control system is modeled, using only one intersection (I1), based on TCPN. A model of modeling of the urban traffic signal control system is illustrated in Fig. 33 and Fig. 34.

Given the model in Fig. 33 and Fig. 34, there are two urban traffic signals for the I1 intersection, which has a controller and sensor for these signals. Each traffic signal has three phases (green, yellow, and red), in addition to a specific period for changing each phase. For switching from the red phase to the green phase a period of 30 seconds was set, from the green phase to the yellow phase a period of 5 seconds was set, and from the yellow phase to the red phase a period of 25 seconds was set. This period was set considering the pedestrians' movements.

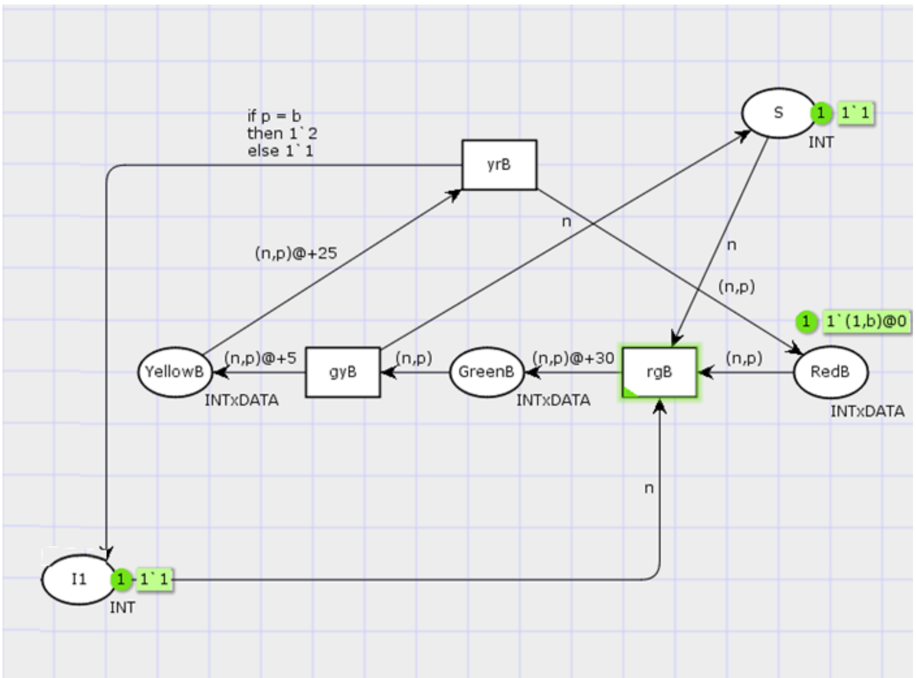
The TCPN model contains eight places, six transitions, eight directed arcs connecting places and transitions, and finally, textual inscriptions next to places, transitions, and arcs, that is,

Figure 33 – TCPN Model for Urban Traffic Signal Control System - Part A of intersection.



Source: the author

Figure 34 – TCPN Model for Urban Traffic Signal Control System - Part B of intersection.



Source: the author

token colors (data values). It is worth mentioning that the entries are written in the programming language CPN ML, an extension of the Standard ML language.

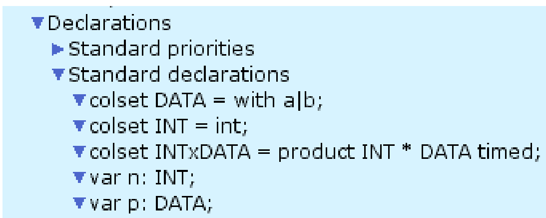
Formal definition of TCPN illustrated in Fig. 35, as well as time restrictions $tm1 = 1'1 + 1'(1,b)@0 + 1'(2,a)@0 + 1'1$; $tm1[1,b]$=0; $tm1[2,a]$=0. For the design of models in Fig. 33 and Fig. 34, it is necessary to define the declarations (sets of colors) illustrated in Fig. 36.

Figure 35 – Formal Definition TCPN for Urban Traffic Signal Control System.

∑ = {INT, DATA, INT x DATA}
P = {I1, S, RedA, YellowA, GreenA, RedB, YellowB, GreenB}
T = {rgA, gyA, yrA, rgB, gyB, yrB}
A = {rgB to GreenB, GreenB to gyB, gyB to YellowB, YellowB to yrB, yrB to RedB, RedB to rgB, S to rgB, gyB to S, yrB to I1, I1 to rgB, I1 to rgA, rgA to GreenA, GreenA to gyA, gyA to YellowA, YellowA to yrA, yrA to RedA, RedA to rgA, yrA to I1}
V = {n: INT, p: DATA, b: DATA, a: DATA}
C (p) = {INT if p ϵ {I1, S} INT x DATA if p ϵ {RedB, GreenB, YellowB, RedA, GreenA, YellowA}
G (t) = Ø
E (a) = {(n, p) if *a* ϵ {(RedB, rgB), (GreenB, gyB), (yrB, RedB), (RedA, rgA), (GreenA, gyA), (yrA, RedA)} (n,p)@+25 if *a* ϵ {(YellowB, yrB), (YellowA, yrA)} (n,p)@+5 if *a* ϵ {(gyB, YellowB), (gyA, YellowA)} (n,p)@+30 if *a* ϵ {(rgB, GreenB), rgA, GreenA)} n if *a* ϵ {(I1, rgB), (I1, rgA), (S, rgB), (gyB, S)} if *p = b* then *1' 2* else *1' 1* if *a* = yrB to I1 if *p = a then 1' 1* else *1' 2* if *a* = yrA to I1
I (p) = { 1' (1, b)@0 if *p* = RedB 1' (2, a)@0 if *p* = RedA 1' 1 if *p* ϵ {I1, S} Ø otherwise

Source: the author

Figure 36 – Color Sets of Urban Traffic Signal Control System Model.

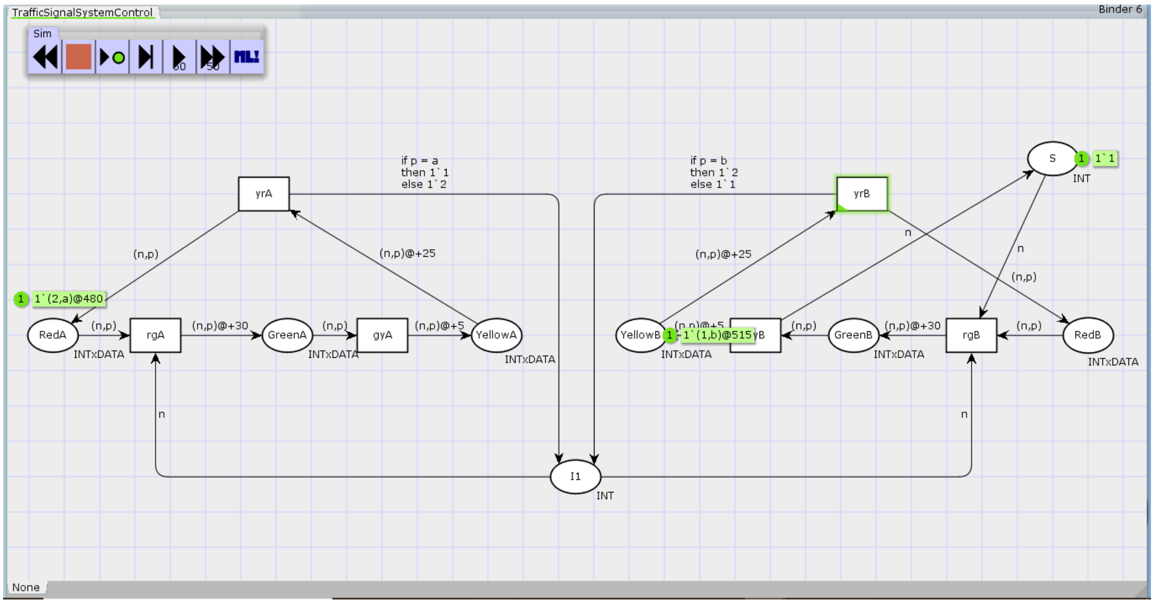


Source: the author

5.2.3 Simulation of the Model

A TCPN model of a system describes the states of the system and the transitions that can cause the system to change. By simulating the TCPN model, it is possible to investigate and explore systems' behavior. The purpose of the simulation is to identify design errors and evaluate the system design. Fig. 37 illustrates the simulations listing 50 stages of the automatic simulation of the urban traffic signal control system.

Figure 37 – Simulation of 50 steps of Urban Traffic Signal Control System.



Source: the author

TCPN networks can be simulated interactively or automatically. During the interactive simulation, the accelerator is on the rise and determines the next step, selecting among them the events activated by the current event. Before and after the automatic simulation, the current token and activated transitions are displayed as described for interactive mode.

5.2.4 Verification of the Model

An important characteristic of TCPNs is the possibility to check the accuracy of the model, that is, to identify the presence or absence of properties. There are many methods for checking CPNs, and they can be classified in different ways (MURATA, 1989), (AALST; STAHL; WESTERGAARD, 2013). The properties that are analyzed to verify the model of the urban traffic signal control system are reachability, safeness, reversibility and home state, boundedness, fairness, and liveness, as well as spatial statistics.

Statistics: Fig. 38 is prepared by CPN Tools and illustrates the first part of the state space report for the TCPN model. Statistics for the graph are also specified, that is, it has 3 nodes and 2 arcs.

Reachability: This property declares that when triggering a transition, it is enabled and it will change the distribution of the token (marking) in a Petri Net according to the transition rule. A sequence of firings will result in a sequence of markings. Therefore, by analyzing the graph of TCPN illustrated in Fig. 39, it is notable that there is correspondence from one marking to another marking between the paths in the state space.

Figure 38 – Statistics of TCPN for Urban Traffic Signal Control System.

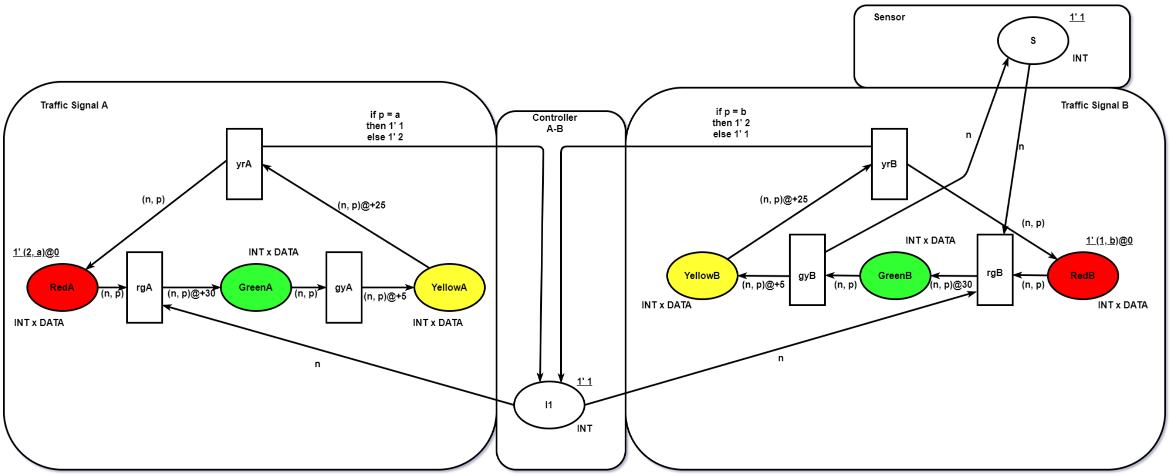
```
 Statistics
------------------------

 State Space
    Nodes:  8
    Arcs:   8
    Secs:   0
    Status: Full

 Scc Graph
    Nodes:  3
    Arcs:   2
    Secs:   0
```

Source: the author

Figure 39 – Graph TCPN for Urban Traffic Signal Control System.



Source: the author

Figure 40 – Reversibility and Home State of TCPN for Urban Traffic Signal Control System.

```
 Home Properties
------------------------------------------

 Home Markings
    Initial Marking is a home marking
```

Source: the author

Safeness: By analyzing the TCPN graph in Figure 39 it can be seen that the number of tokens never exceeds one for all possible possibilities. A Petri Net is declared secure if all places in the Net are secure.

Reversibility and Home State (Home Marking): Fig. 40 is obtained from CPN Tools and illustrates the part of the state space report specifying the home properties, that is, there is a single home marking which is an initial marking.

Boundedness: This property provides information on how places' tokens can contain all reachable markings, that is, how many and which tokens a place can contain when all reachable markings are considered. Fig. 41 is obtained from CPN Tools and illustrates the part of the state space report that specifies the best upper and lowers integer limits. The best integer upper limit for a place specifies the maximum number of tokens that can reside in that place in any reachable marking.

Figure 41 – Best Integer Bounds of TCPN for Urban Traffic Signal Control System.

```
 Boundedness Properties
------------------------------------------------------------

  Best Integer Bounds
                                             Upper      Lower
     TrafficSignalSystemControl'GreenA 1       1          0
     TrafficSignalSystemControl'GreenB 1       1          0
     TrafficSignalSystemControl'I1 1           1          0
     TrafficSignalSystemControl'RedA 1         1          0
     TrafficSignalSystemControl'RedB 1         1          0
     TrafficSignalSystemControl'S 1            1          0
     TrafficSignalSystemControl'YellowA 1      1          0
     TrafficSignalSystemControl'YellowB 1      1          0
```

Source: the author

The best upper integer limit for GreenA, GreenB, I1, RedA, RedB, S, YellowA, and YellowB places is 1, which means that there is at most one token in those places and that there is a reachable marking where there is a token in those places. This is what one would expect since these places are always supposed to contain a single token with a color corresponding to data received up to that point, as these are single elements in the infrastructure.

Figure 42 – The Best Upper Multiset Bounds of TCPN for Urban Traffic Signal Control System.

```
  Best Upper Multi-set Bounds
     TrafficSignalSystemControl'GreenA 1    1`(2,a)
     TrafficSignalSystemControl'GreenB 1    1`(1,b)
     TrafficSignalSystemControl'I1 1        1`1++
                                            1`2
     TrafficSignalSystemControl'RedA 1      1`(2,a)
     TrafficSignalSystemControl'RedB 1      1`(1,b)
     TrafficSignalSystemControl'S 1         1`1
     TrafficSignalSystemControl'YellowA 1   1`(2,a)
     TrafficSignalSystemControl'YellowB 1   1`(1,b)
```

Source: the author

Fig. 42 depicts the best upper multiset limit for a place, which specifies for each color in the color set of the place the maximum number of tokens that are contained in that place with the color provided in any reachable marking. This is specified as a multiset, where the coefficient for each value is the maximum number of tokens with the given value, for example, places GreenB, RedB, YellowB are assigned the value 1'(1,b).

Figure 43 – The Best Lower Multiset Bounds of TCPN for Urban Traffic Signal Control System.

```
Best Lower Multi-set Bounds
   TrafficSignalSystemControl'GreenA 1    empty
   TrafficSignalSystemControl'GreenB 1    empty
   TrafficSignalSystemControl'I1 1        empty
   TrafficSignalSystemControl'RedA 1      empty
   TrafficSignalSystemControl'RedB 1      empty
   TrafficSignalSystemControl'S 1         empty
   TrafficSignalSystemControl'YellowA 1   empty
   TrafficSignalSystemControl'YellowB 1   empty
```

Source: the author

Fig. 43 depicts the best lower multiset limit for a place, which specifies for each color in the color set of the place, the minimum number of tokens that are contained in that place with the color provided in any reachable marking. This is specified as a multiset, where the coefficient for each value is the minimum number of tokens with the given value. The best lower multiset limit, therefore, provides information about how many tokens of each color are always present in a given place. For example, all places have empty multiset as their best lower multiset limit. This means that token colors are not always present in these places. However, it is not possible to conclude that there are markups reachable without tokens in these places.

Fairness: This property is used to discard behaviors where a process can wait indefinitely before being activated. Fig. 44 is obtained from CPN Tools and illustrates that the part of the state space report specifying information on the frequency with which the transitions fire, that is, a list of transitions that are impartial. A transition is impartial if it occurs with infinite frequency in all infinite occurrence sequences. This implies that removing the transition will remove all infinite occurrence sequences from the TCPN model, for example, gyA, gyB, rgA, rgB, yrA, yrB are unbiased transitions. It also means that there are now only transition instances and transition instances with no fairness.

Liveness: This property declares that for any accessible marking there is at least one enabled transition allowing the system to evolve. Fig. 45 is obtained from CPN Tools and illustrates that there is no dead marking, that is, a marking in which no connection element is activated. It also means that there are no dead transitions, that is, each transition can be fired at least once. It also means that all transitions are alive, that is, a transition is active if, starting from any reachable marking, whenever one can find a sequence of occurrences containing the transition, it is possible to fire the transition later.

Figure 44 – Fairness of TCPN for Urban Traffic Signal Control System.

```
 Fairness Properties
------------------------------------------

  Impartial Transition Instances
     TrafficSignalSystemControl'gyA 1
     TrafficSignalSystemControl'gyB 1
     TrafficSignalSystemControl'rgA 1
     TrafficSignalSystemControl'rgB 1
     TrafficSignalSystemControl'yrA 1
     TrafficSignalSystemControl'yrB 1

  Fair Transition Instances
     None

  Just Transition Instances
     None

  Transition Instances with No Fairness
     None
```

Source: the author

Figure 45 – Liveness of TCPN for Urban Traffic Signal Control System.

```
 Liveness Properties
--------------------------------

  Dead Markings
     None

  Dead Transition Instances
     None

  Live Transition Instances
     All
```

Source: the author

6
Conclusion

Modern life in cities is highly dependent on infrastructures such as road, rail, and air traffic, energy, water supply, and waste. These infrastructures are highly demanded by citizens and organizations, and their design and maintenance are crucial to our daily activities. These infrastructures present high complexity and demand, which leads to the need to apply ICTs and IoT for their design, control, and management. For this reason, a smart city usually refers to the search and identification of intelligent solutions that allow modern cities to improve the quality of services provided to citizens.

Modeling infrastructure real-time control systems in a smart city is a complex activity. There is no single standard to be used, since there are many different system activities to be performed, including modeling, simulation, and property verification, and since there are many modeling languages proposed in recent years that are mostly not adapted to express the terminology of stakeholders.

The SmartCitySysML profile is proposed to meet the needs of management, operation, and decision-making, as well as the basis for designing software solutions for smart cities through urban data modeling so that various information services are related and provided to different users. The SmartCitySysML profile is applied to model useful elements for a real-time distributed system for the control of urban traffic signal, more specifically, the control of interconnected traffic signal is providing a visual model of a smart city system. The SysML diagrams chosen to be expanded are Sequence (SD), Requirements (REQ), Block Definition (BDD), and Internal Block (IBD).

The dimensions of smart cities are identified and described from essential factors and characteristics to improve the efficiency, sustainability, and quality of life of citizens living in these cities. The design of these proposed dimensions was carried out from the extension of the SmartCitySysML profile. The SysML Internal Block Diagram (IBD) is used to model them as native elements of the system design of a smart city, separate interests, and improve the focus on problem-solving. This design provides the use of common terminology known to stakeholders who are responsible for managing a variety of aspects of a smart city.

The case study details the modeling of an urban traffic signal control system by specifying characteristics related to traffic signal control to better understand the problem and describe the use of SysML extensions to model the problem. For modeling the urban traffic control system first the functional requirements and the region were defined. Next, the SysML Sequence (SD), Requirements (REQ) and Block Definition diagrams (BDD), and the SmartCitySysML profile were used to model the previously defined region. Next, the basic architectural elements of the urban traffic control system, i.e., sensor, controller, and actuator were modeled separately as Petri Net sub-models to describe the behavior of each of these elements. Finally, a model with Timed Coloured Petri Nets (TCPN) is developed to evaluate the properties of the model through simulation and formal verification.

The formal modeling elaborated for the urban traffic signal control system was designed from the SysML Block Definition diagram and the SmartCitySysML profile. For modeling the basic architectural elements of the urban traffic control system, Petri Net sub-models were designed for each element (sensor, controller, and actuator) to describe separately the behavior of each of these elements. For the simulation and verification of the behavioral properties of the urban traffic control system, a TCPN model is designed from the Petri Net sub-models of the basic architectural elements of an urban traffic control system.

In brief, this dissertation presented the SmartCitySysML profile, the design of the dimensions of a smart city using the SmartCitySysML profile, the integration of SysML with the Timed Coloured Petri Nets (TCPN) to model the case study, i.e., an urban traffic signal control system for a group of intersections, providing a visual model of a smart city system.

6.1 Research Limitations and Challenges

For the design of both the SmartCitySysML profile and the extension of the SmartCitySysML profile to smart city dimensions, some challenges and limitations of SysML emerged related to formalism and consistency between diagrams, mainly due to the lack of software tools that can fully implement all the features of SysML. Also, SysML does not allow for formal modeling and mathematical analysis to verify good systems properties.

In the design for smart city dimensions, SysML is used to model elements of systems that are not software, i.e., elements of smart city dimensions at a higher level of granularity in a complex system. Furthermore, based on the literature, factors, and characteristics of smart cities, it was possible to note that the people, economy, environment, mobility, living, and governance are not yet consolidated into the dimensions of a smart city.

6.2 Threats to validity

Threats to validity may limit the ability to interpret and/or describe results from the data obtained. Therefore, there is no way to disregard the following threats found in this dissertation.

- Validity Construction: The search string used to find related works (Chapter 2, Section 2.5) might not fully cover the areas of Smart Cities, SysML, and Timed Coloured Petri Nets associated with modeling a profile. To mitigate this threat, a string was made as comprehensive as possible in terms that would be utilized in the world, using various synonyms. Furthermore, the SmartCitySysML profile, the extension of the SmartCitySysML profile to smart city dimensions, the modeling of a smart city application, i.e., urban traffic signal control system, and therefore the verification of the behavioral properties of this modeling were elaborated from the aspects associated with any city.
- Internal Validity: The researcher was responsible for extracting and classifying the info from each article utilized in this dissertation, therefore, biases or problems in data extraction may threaten the validity of the info characterization. Initially, articles were included or excluded consistently with the researcher's judgment. Consequently, studies may are categorized incorrectly. To mitigate this threat, the choice and extraction reviews were done using snowball sampling. There are selected articles that did not make it clear how they obtained the dataset to perform a sensible city profile, and/or elaborate the modeling for a sensible city application employing a profile, and/or the way to verify behavioral properties of the modeling elaborated for a sensible city application. To mitigate these biases, the references of the articles were accessed and evaluated for such information.
- External Validity: It cannot be said that the survey of articles covered the whole area of computer science because there is not a big number of scientific articles that address the topics of smart cities, SysML, and Timed Coloured Petri Nets for the elaboration of a profile for smart cities, modeling of an application for smart cities and therefore the formal verification, i.e., verification of behavioral properties of this modeling. To mitigate this threat, the research sequence was created to succeed in as many papers as possible. In addition, this dissertation presented evidence of the most parts of a city used to develop the SmartCitySysML profile, the modeling of a sensible city application (urban traffic signal control system) using the SmartCitySysML profile, and therefore the formal verification of the modeling of the urban traffic signal control system, also as identified gaps to be explored and function as a guide for future work.

6.3 Contributions

This research resulted in the publication of the following works:

- SOUZA, L. S.; MISRA, S.; SOARES, M. S. *"SmartCitySysML: A SysML Profile for SmartCities Applications"* published in *The 20th International Conference on Computational Science and Its Applications* (ICCSA 2020), classified by CAPES as *Qualis* A3.

- *"Design of Smart Cities Dimensions using a SmartCitySysML Profile"* published in *The 21st International Conference on Computational Science and its Applications* (ICCSA 2021), classified by CAPES as *Qualis* A3.

- *"Combining SysML with Petri Nets for the Design of an Urban Traffic Signal Control"* published in *The 21st International Conference on Computational Science and its Applications* (ICCSA 2021), classified by CAPES as *Qualis* A3.

This research resulted in the submission of the following works:

- *"Combining SysML and Timed Coloured Petri Nets for Designing Smart City Applications"* submitted to *Systems Engineering*, classified journal by CAPES as *Qualis* A4.

6.4 Future Works

In this dissertation, the extension of the SysML profile for smart cities, named SmartCitySysML, has been described. The SmartCitySysML profile can be used to perform modeling of systems, e.g., real-time systems or health information systems, considering the quality of the diagrams from a practical point of view. In the case study, i.e., urban traffic control system, Petri Nets sub-models are developed to separately model the behavior of the basic architectural elements (sensor, controller, and actuator) of this system. In addition to these Petri Nets sub-models, a Timed Coloured Petri Nets (TCPN) model is also designed from the union of these sub-models to verify behavioral properties through simulation, as well as to identify possible faults and correct the functions of a system.

It is intended for future work to use the SmartCitySysML profile to model other case studies, for example, in the domain of health information systems, water and wastewater treatment, energy, and other real-time systems. After the elaboration of these case studies, the simulation was performed with CPN Tools to verify functionalities, completeness, consistency, and correctness of these models, as well as to evaluate the performance and behavioral properties aiming to identify possible flaws and correct the functions of these models before the system is deployed.

It is also intended to define the functional requirements for the urban traffic signal control system to ensure safety, usability, reliability, performance, efficiency, interoperability, and among others.

Other future work may be to analyze the scenarios from this case study by integrating Petri Net and other case studies with the practice of software development of autonomous and intelligent systems. One can provide modeling using SmartCitySysML profile to software developers, and then evaluate the quality of the diagrams from a practical point of view.

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